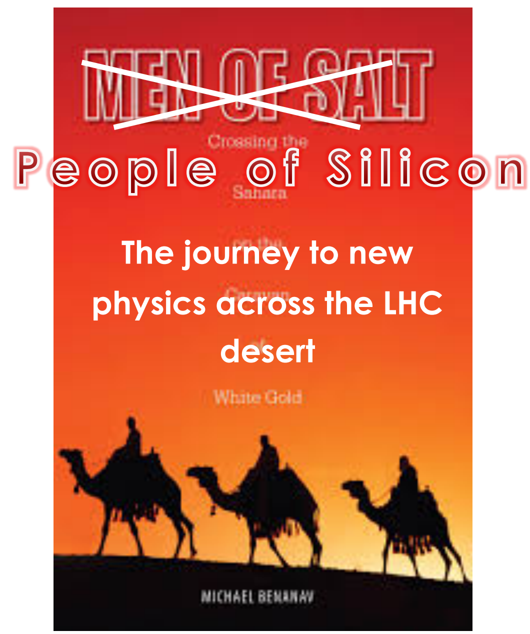
Tracking particles in space and time

Besides a few indirect signals of new physics, particle physics today faces an extraordinary drought.

We need to cross an **energy- cross section** desert to reach the El-dorado of new physics.

Very little help in the direction of this path is coming from nature, the burden is on the accelerator and experimental physicists to provide the means for this crossing.

Timing is one of the enabling technologies to cross the desert



The effect of timing information

The inclusion of track-timing in the event information has the capability of changing radically how we design experiments.

Timing can be available at different levels of the event reconstruction, in increasing order of complexity:

1) Timing in the event reconstruction ➔ **Timing layers**
    - this is the easiest implementation, a layer ONLY for timing
2) Timing at each point along the track ➔ **4D tracking**
    - tracking-timing
3) Timing at each point along the track at high rate ➔ **5D tracking**
    - Very high rate represents an additional step in complication, very different read-out chip and data output organization

One sensor **does not** fit all

Silicon sensors for tracking come in many shapes, fitting very different needs:

- **Spatial precision:** from a few microns to mm (pixels, strips)
- **Area:** from mm^2 up to hundred of square meter
- **Radiation damage:** from nothing to >1E16 n_{eq}/cm^2 (3D, thin planar, thick planar)

Likewise, Silicon sensors for time-tracking are being developed to fit different needs with respect of time and space precision. The geometries above are combined with:

- Very high time precision ~ 30-50 ps per plane
- Good time precision ~ 50-100 ps per plane

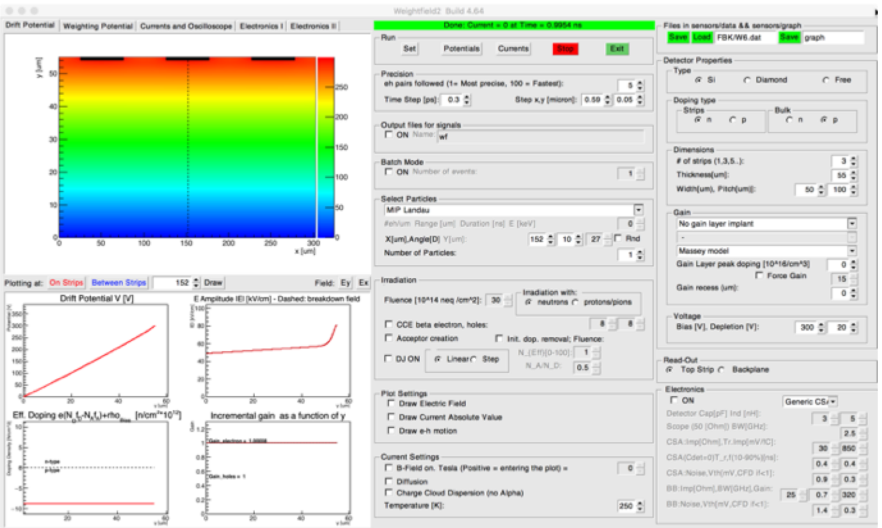
Preamble: simulator Weightfield2

Available at:

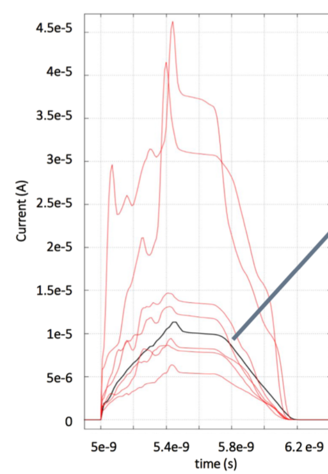
http://personalpages.to.infn.it/~cartigli/Weightfield2/Main.html

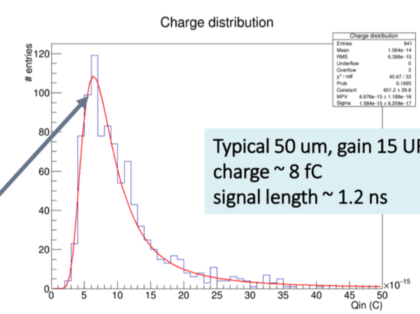
It requires Root build from source, it is for Linux and Mac.

It will not replace TCAD, but it helps in understanding the sensors response



50 um UFSD signals



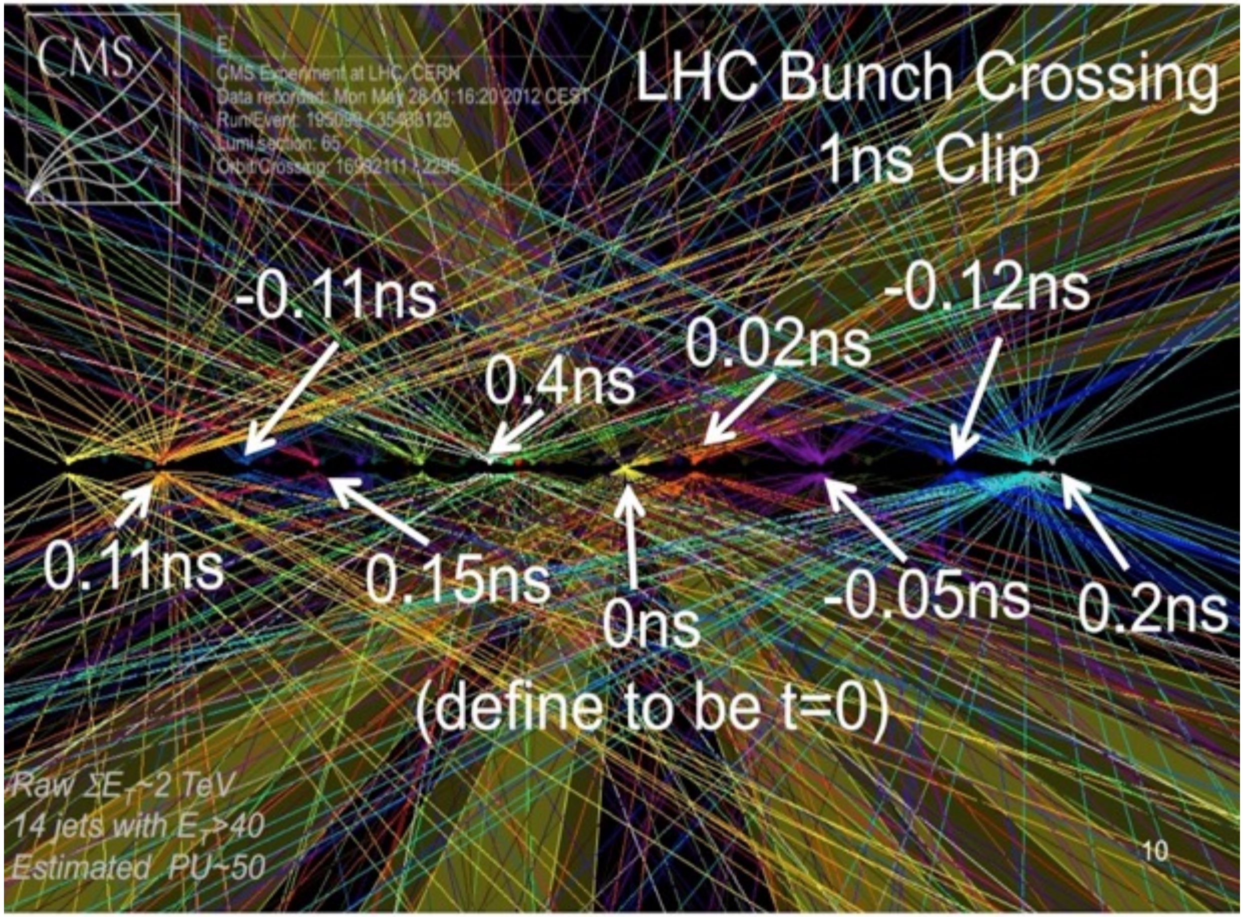


Typical 50 um, gain 15 UFSD MIP signal
charge ~ 8 fC
signal length ~ 1.2 ns

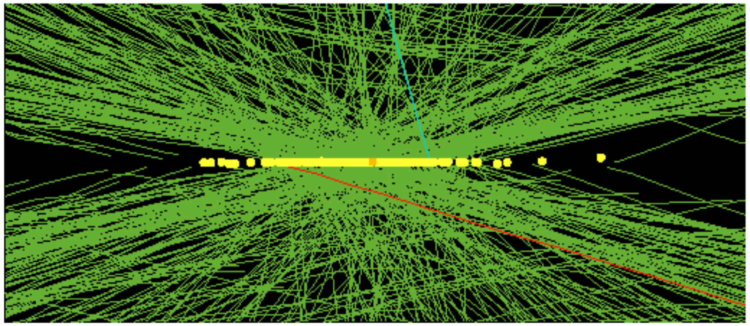
We have a fast sensor providing steep signals

➡ we need a fast readout electronics to reach the best time re

Current situation at LHC: no real need for timing

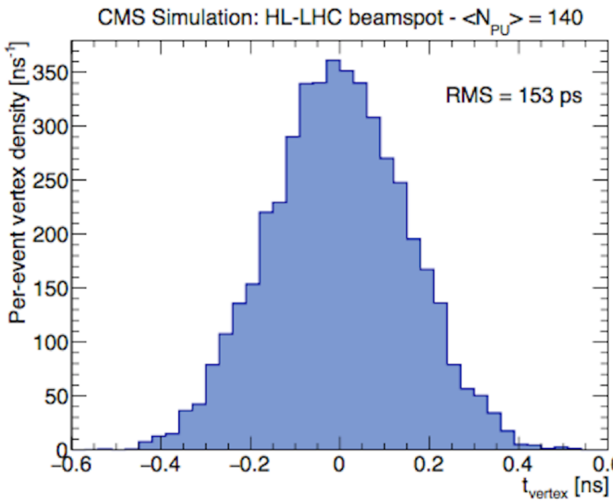


Is timing really necessary at HL-LHC?



The research into 4D tracking is strongly motivated by the HL-LHC experimental conditions:

150-200 events/bunch crossing

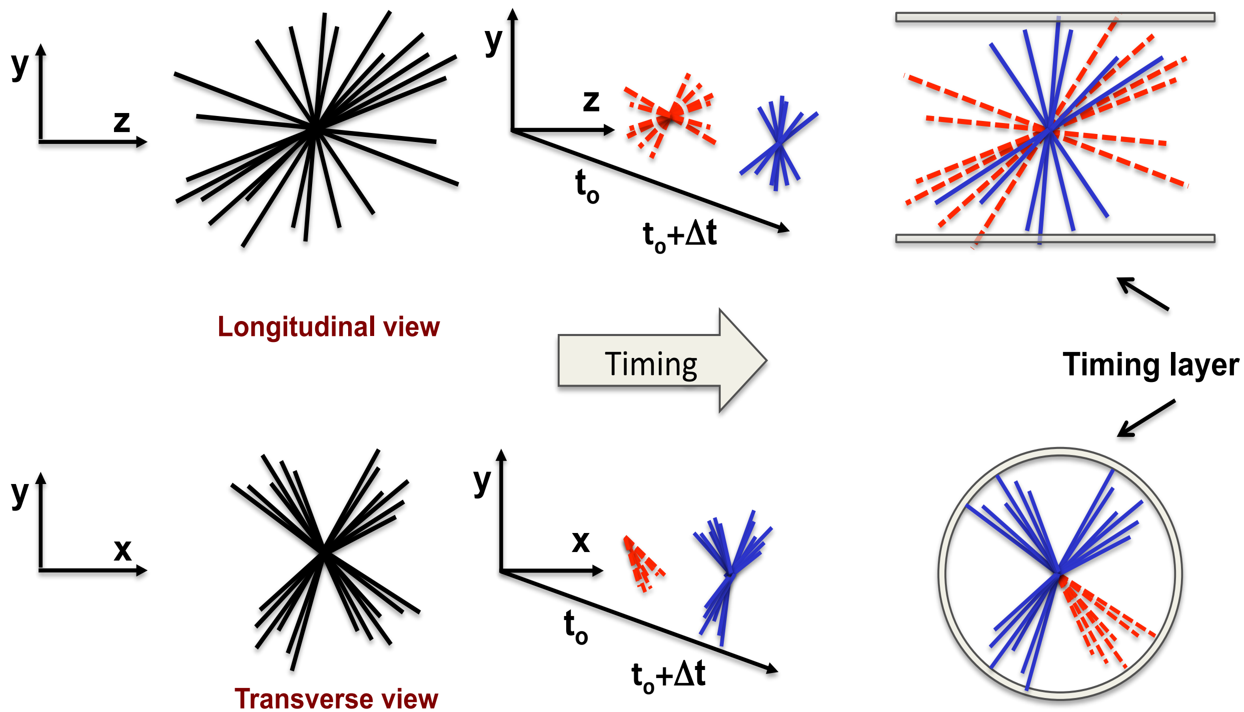


According to CMS simulations:

- **Time RMS between vertexes: 153 ps**
- **Average distance between two vertexes: 500 um**
- **Fraction of overlapping vertexes: 10-20%**
    - Of those events, a large fraction will have significant degradation of the quality of reconstruction

At HL-LHC: Timing is equivalent to additional luminosity

One extra dimension: tracking in 4Dimension

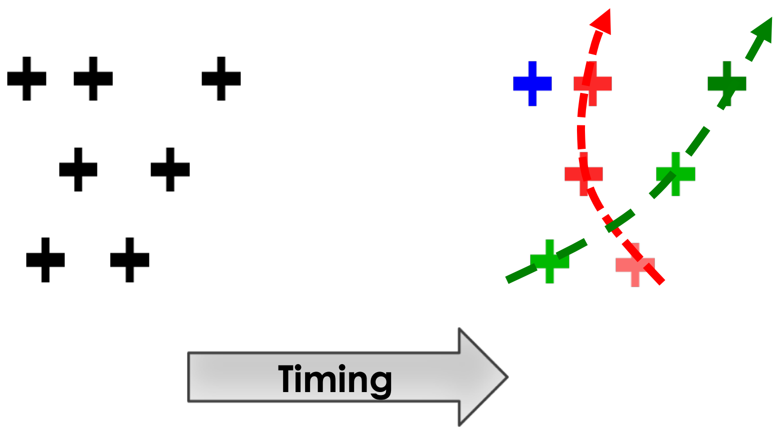


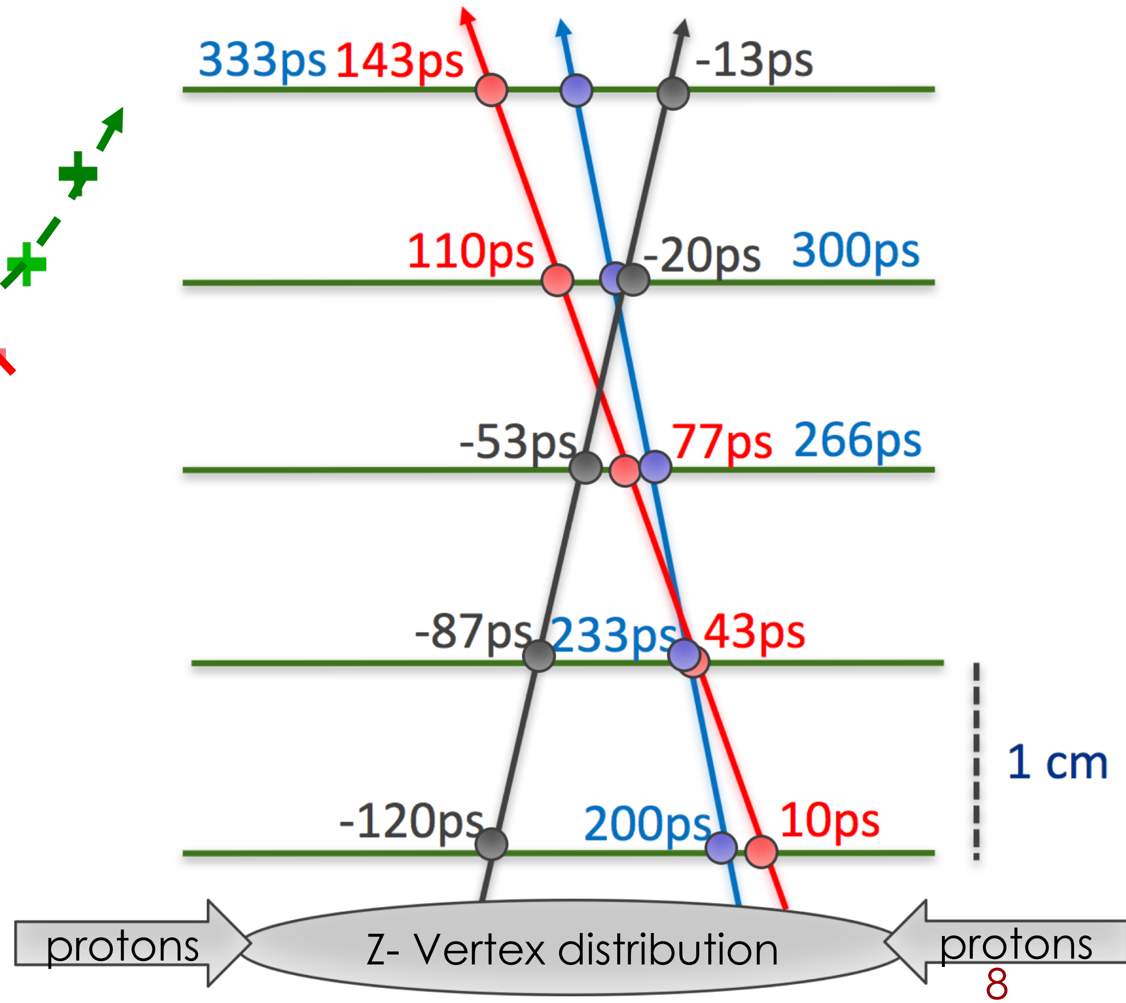
Timing complements tracking in the correct reconstruction of the events

4D tracking: Timing at each point

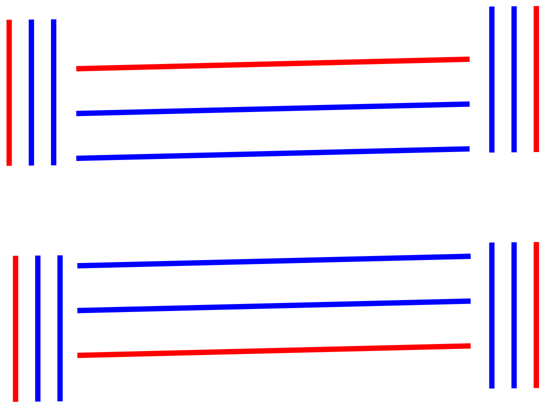
➔Massive simplification of patter recognition, new tracking algorithms will be faster even in very dense environments

➔ Use only "time compatible points"

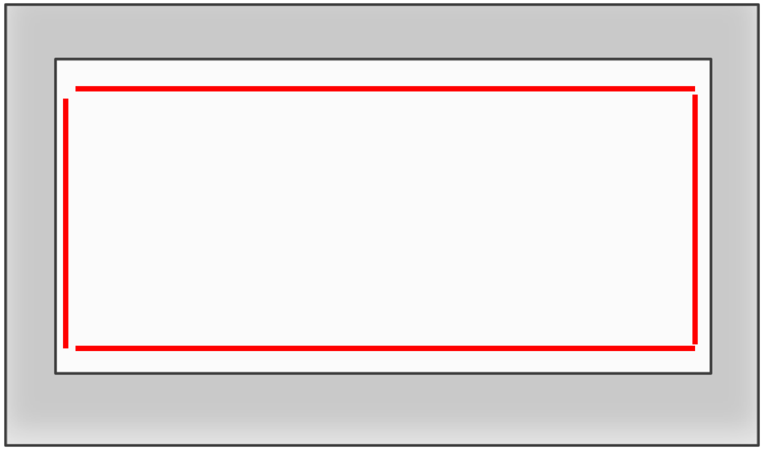




3+1 tracking: tracker + timing layer



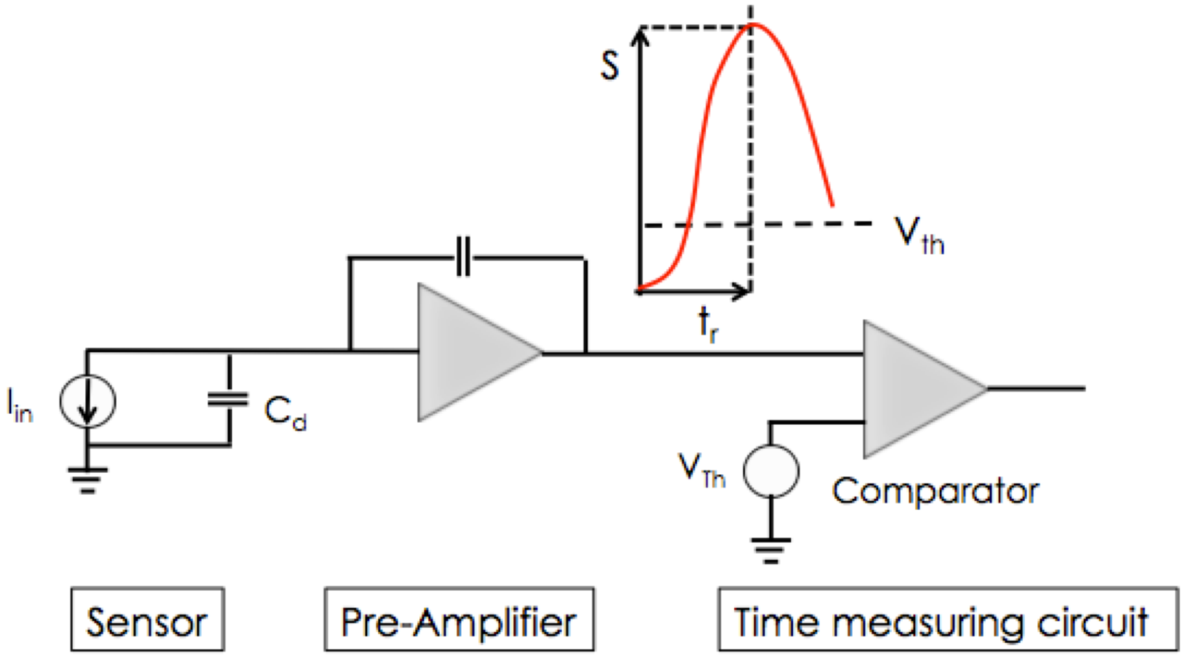
Dedicated Layer(s) in the tracking



Dedicated detector

Silicon time-tagging detector

(a simplified view)



Time is set when the signal crosses the comparator threshold

The timing capabilities are determined by the characteristics of the signal at the output of the pre-Amplifier and by the TDC binning.

Strong interplay between sensor and electronics

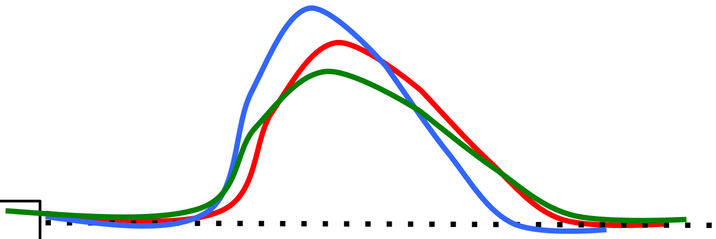
Good time resolution needs very uniform signals

Signal shape is determined by Ramo's Theorem:

$$i \propto q v E_w$$

Drift velocity

Weighting field



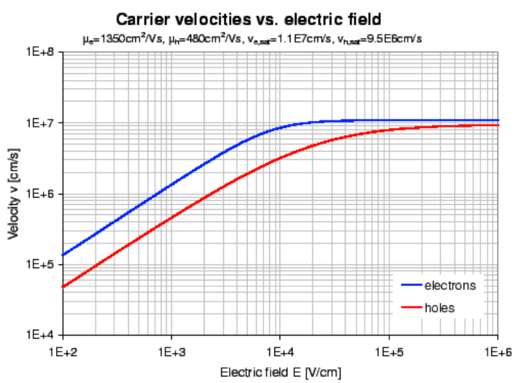
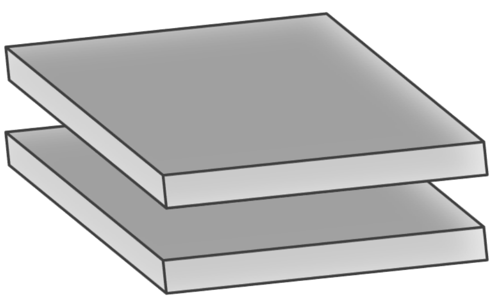


Figure: Electron and hole velocities vs. the electric field strength in silicon.

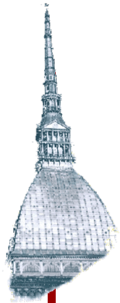


The key to good timing is the uniformity of signals:

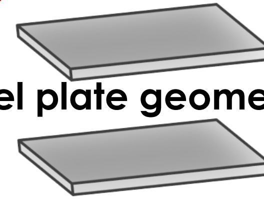
Drift velocity and Weighting field need to be as uniform as possible

Basic rule: parallel plate geometry

Time resolution



$$\sigma_t^2 = \left(\frac{Noise}{dV/dt}\right)^2 + (\Delta ionization)^2 + (\Delta shape)^2 + (TDC)^2$$



parallel plate geometry

Subleading, ignored here

Usual **"Jitter"** term

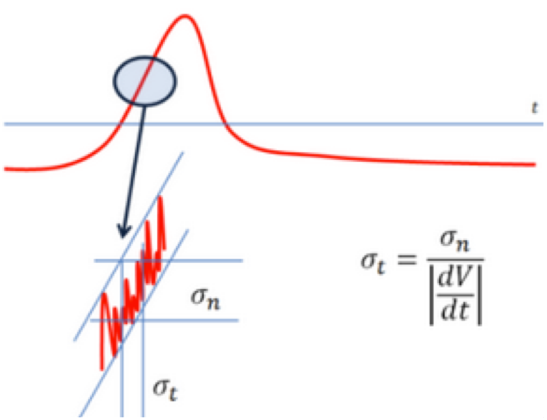
Here enters everything that is "Noise" and the steepness of the signal

Time walk:

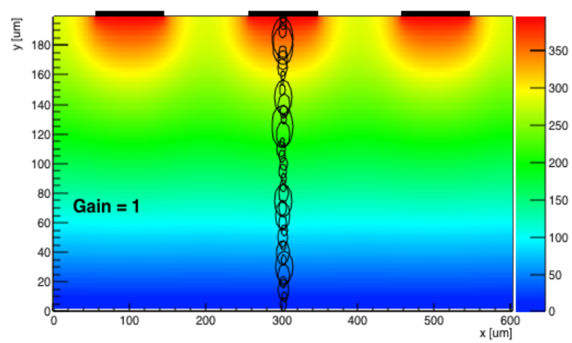
Amplitude variation, corrected in electronics

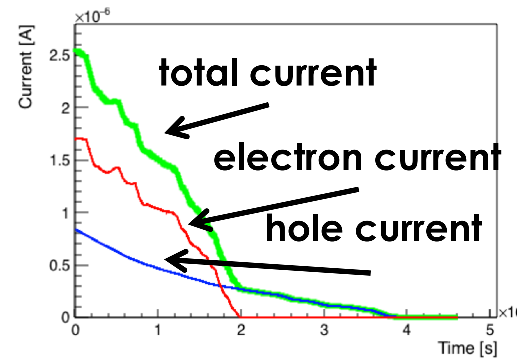
Shape variations:

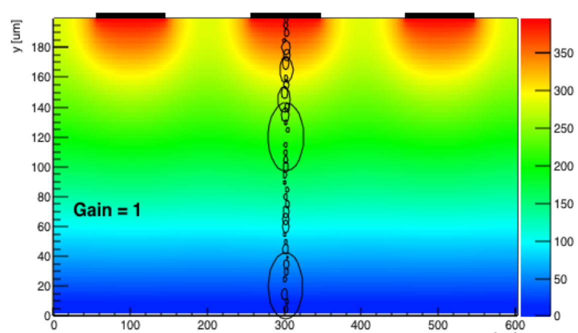
non homogeneous energy deposition

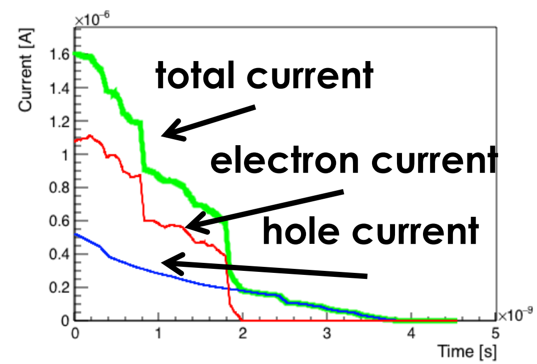


Need large dV/dt







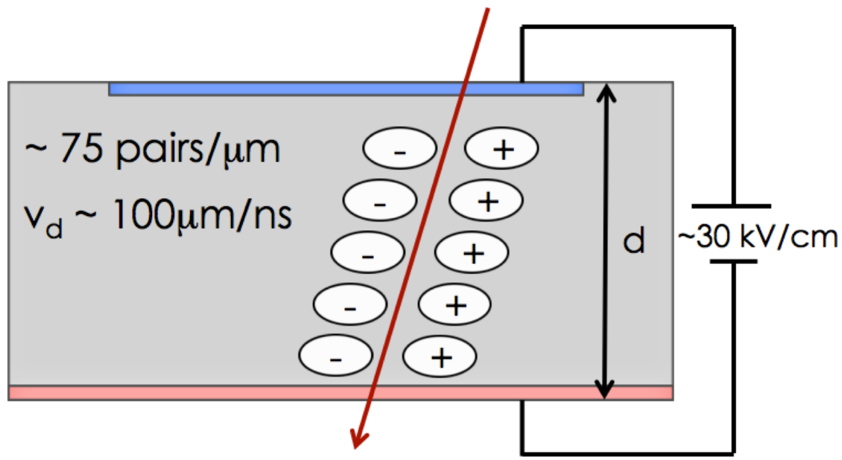


Signal formation in silicon detectors

We know we need a large signal, but **how is the signal formed?**

What is controlling the slew rate?

$$\frac{dV}{dt} \propto ?$$



A particle creates charges, then:

- The charges start moving under the influence of an external field
- The motion of the charges induces a current on the electrodes
- The signal ends when the charges reach the electrodes

What is the signal of one e/h pair?

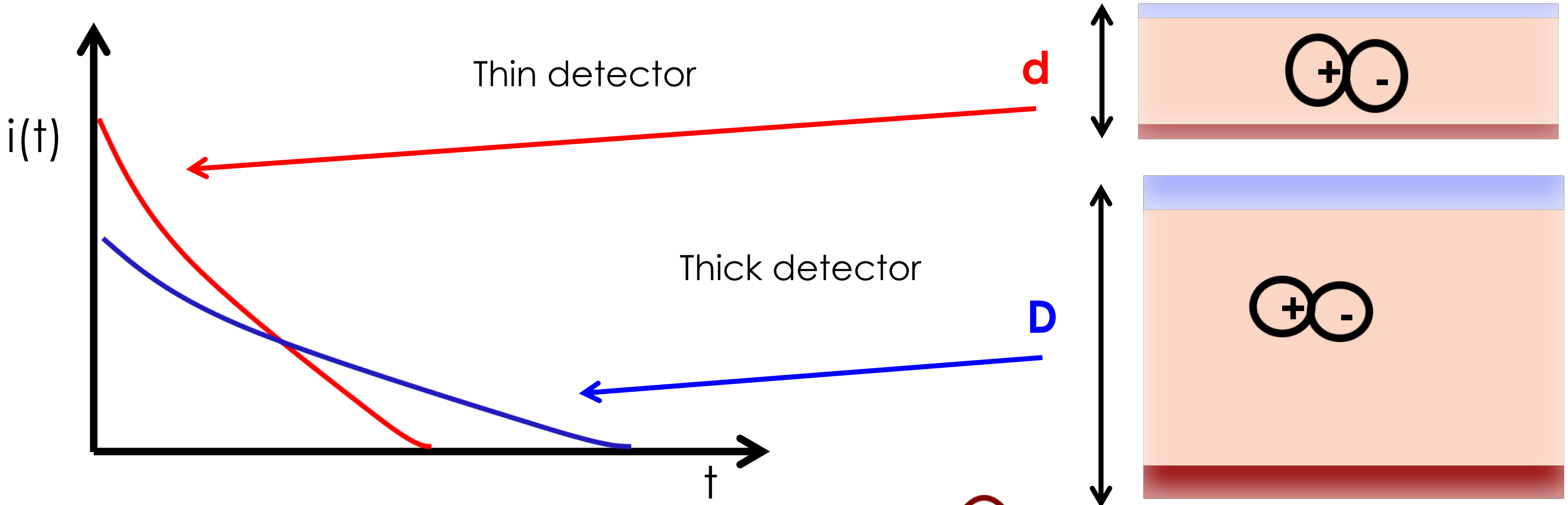
(Simplified model for pad detectors)

Let's consider **one single electron-hole pair.**

The integral of the current is equal to the electric charge, q:

$$\int [i_{el}(t)+i_h(t)]dt = q$$

However **the shape of the signal depends on the thickness** d: thinner detectors have higher slew rate



➔ **One e/h pair generates higher current in thin detectors**

$$i \propto qv\frac{1}{d}$$

Weighting field

Large signals from thick detectors?

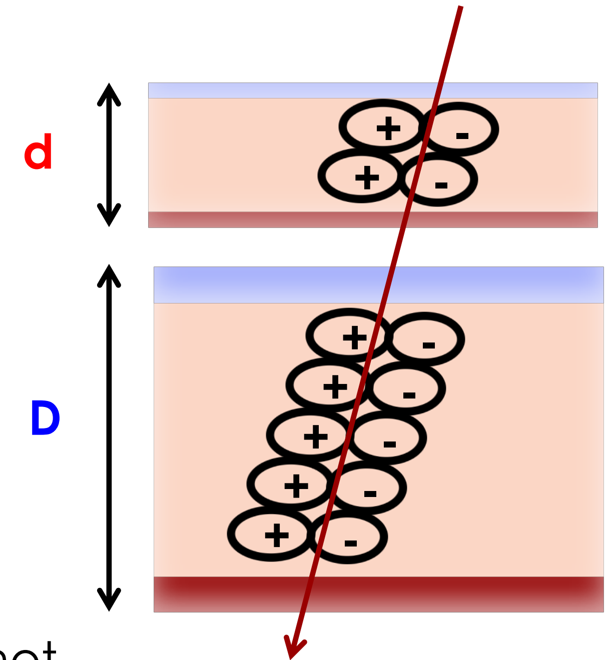
(Simplified model for pad detectors)

Thick detectors have higher number of charges:

$$Q_{tot} \sim 75\ q{*}d$$

However each charge contributes to the initial current as:

$$i \propto qv\frac{1}{d}$$



The initial current for a silicon detector does not depend on how thick (d) the sensor is:

$$i = Nq\frac{k}{d}v = (75\cancel{d}q)\frac{k}{\cancel{d}}v = 75kqv \sim 1-2*10^{-6}\,A$$

Number of e/h = 75/micron

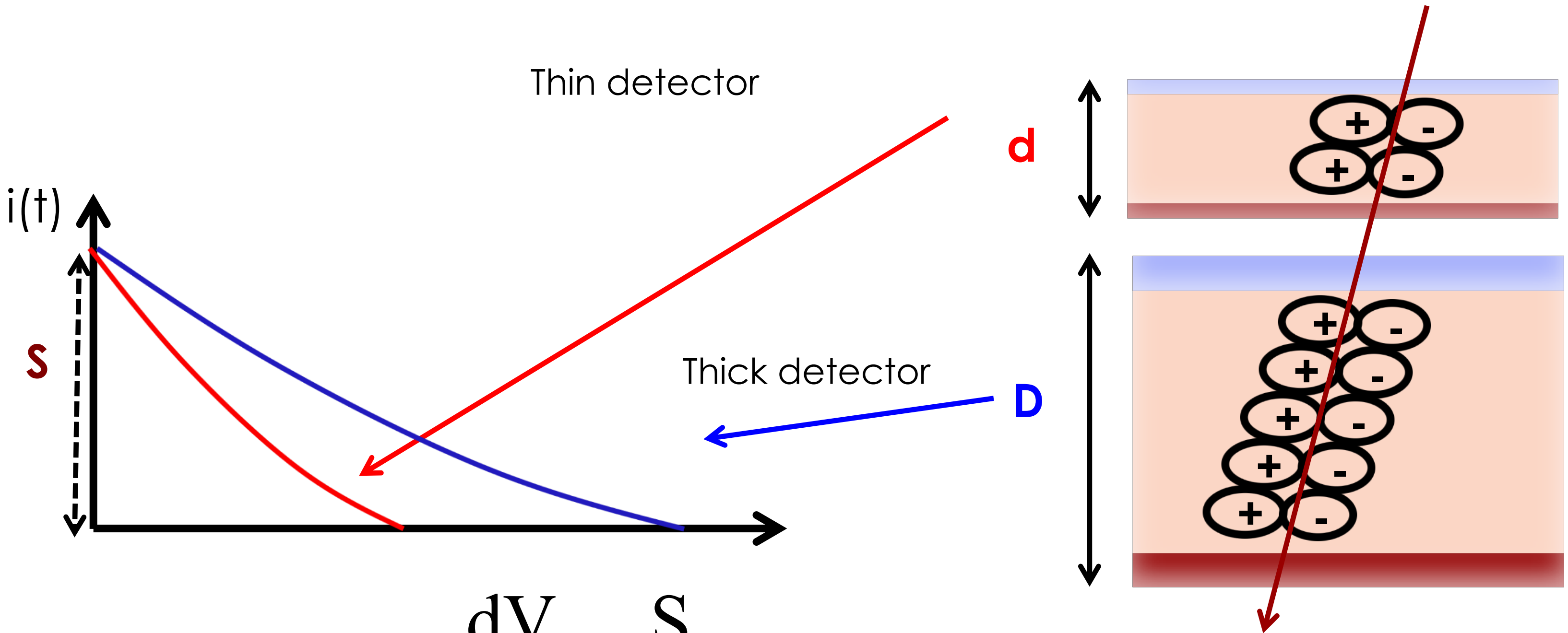
Weighting field

velocity

➔ Initial current = constant

Summary "thin vs thick" detectors

(Simplified model for pad detectors)



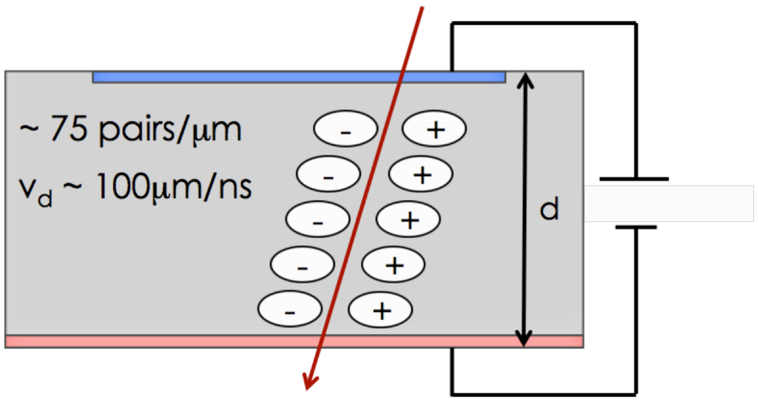
$$\frac{dV}{dt} \sim \frac{S}{t_r} \sim \text{const}$$

Thick detectors have longer signals, not higher signals

We need to add gain

Gain needs E ~ 300kV/cm. How can we do it?

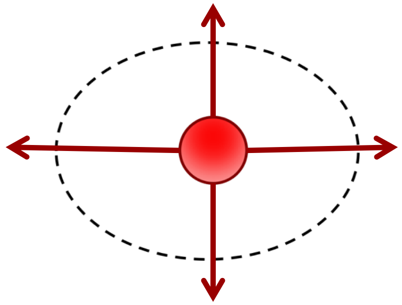
1) Use external bias: assuming a 50 micron silicon detector, we need $\mathbf{V_{bias}}$ **= ~ 600 - 700 V**



Difficult to achieve

2) Use Gauss Theorem:

$$\sum q = 2\pi r * E$$



E = 300 kV/cm ➔ q ~ 10^{16} /cm^3

Need to have 10^{16}/cm^3 charges !!

Gain in Silicon detectors

Gain in silicon detectors is commonly achieved in several types of sensors. It's based on the avalanche mechanism that starts in high electric fields: V ~ 300 kV/cm

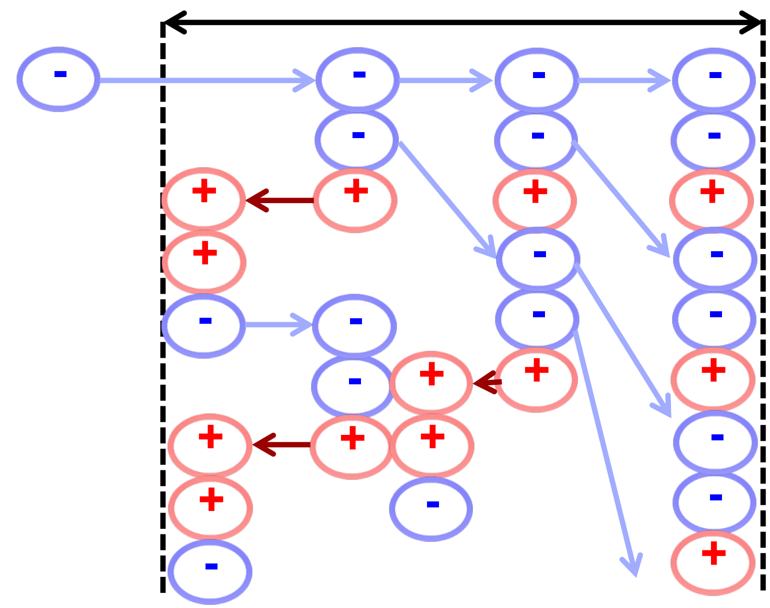
Gain definition:

$$G = e^{\alpha\, l}$$

α = it is the inverse of a distance, strong function of E

$$\alpha_{e,h}(E) = \alpha_{e,h}(\infty) * \exp\left(-\frac{b_{e,h}}{|E|}\right)$$

ΔV ~ 300 kV/cm



Concurrent multiplication of electrons and holes generate very high gain

Silicon devices with gain:

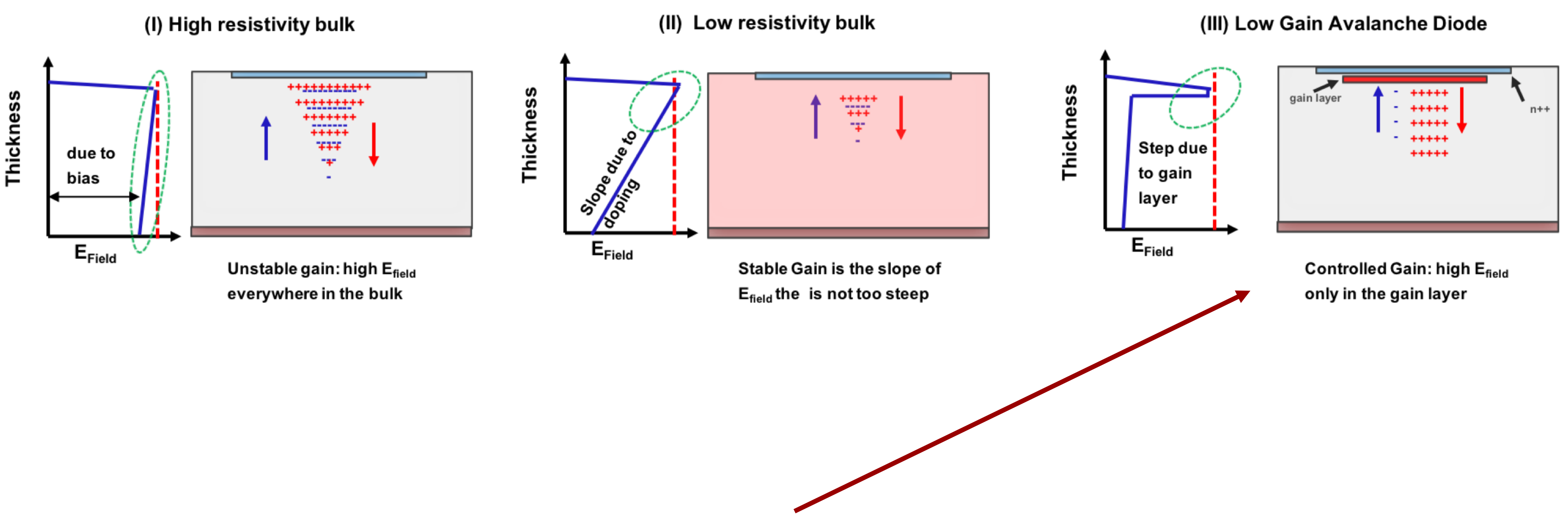
- **APD: gain 50-500**
- **SiPM: gain ~ 10^4**

Electric fields in Silicon sensors

Gain happens when the E_{field} is near the critical values, 300 kV/cm

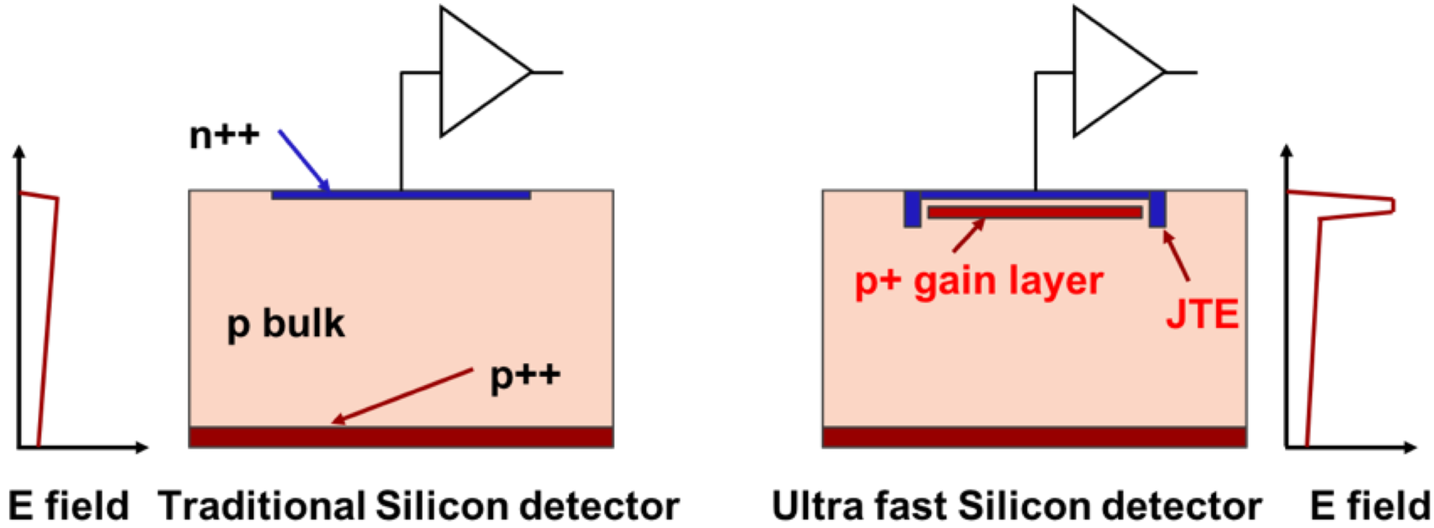
3 methods to increase Efield:

1. Doping in the bulk
2. Doping in the gain layer
3. Bias



- The "low gain avalanche diode" offers the most stable situation
- Gain due to interplay between gain layer and bias

Standard vs Low Gain Avalanche Diodes



The LGAD sensors, as proposed and manufactured by CNM

(National Center for Micro-electronics, Barcelona):

High field obtained by adding an extra doping layer

E ~ 300 kV/cm, closed to breakdown voltage

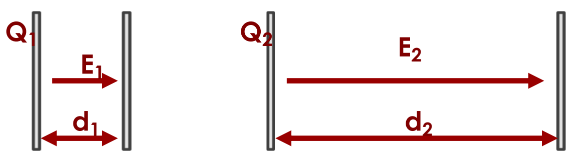
Gain layer

a parallel plate capacitor with high field

Different producers use different designs, implanting the gain layer at different depth.

- **The doping of the gain layer is equivalent to the charge on the plates of the capacitor.**
- **Bias adds additional E field to the Efield due to doping**
- **In deeper gain layer, the part of Efield due to bias is more important**

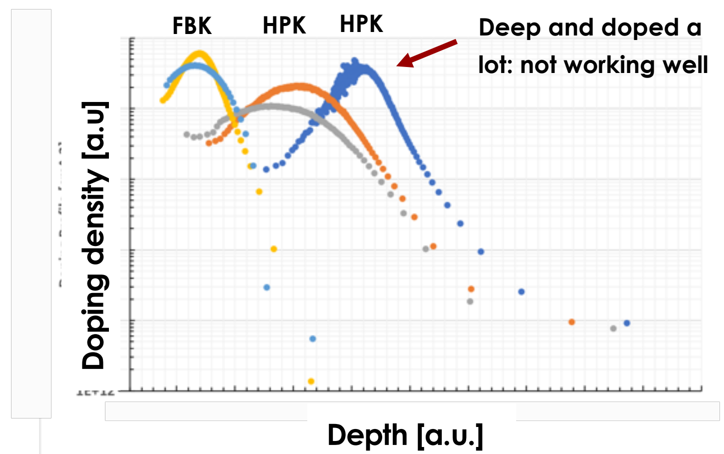
In a parallel plate capacitor, the field **E** does not depend on the distance **d**, only on the charge **Q**



If $Q_1 = Q_2$, then $E_1 = E_2$

$$G \propto e^{\alpha * d}$$

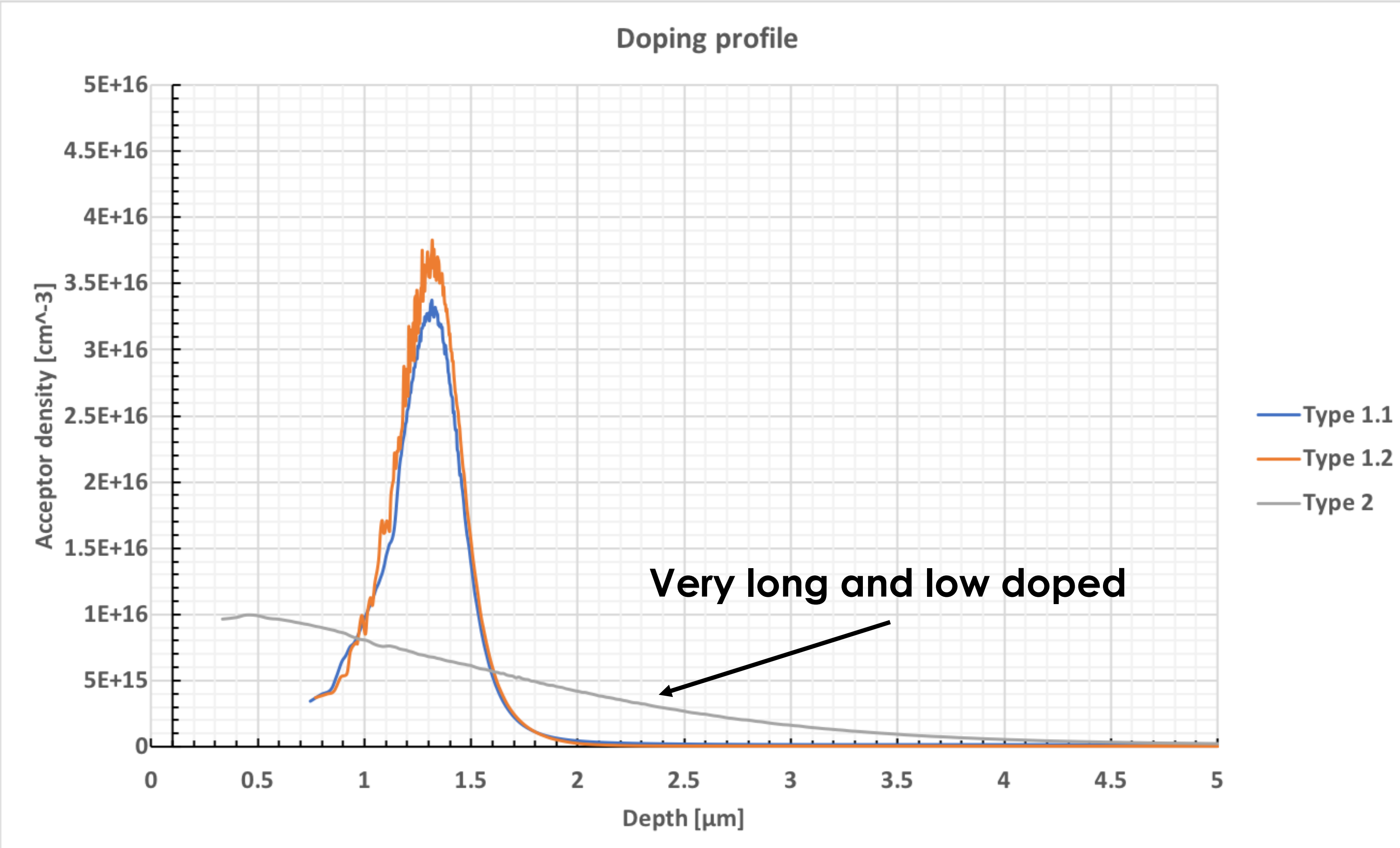
Gain: exp(field * distance)



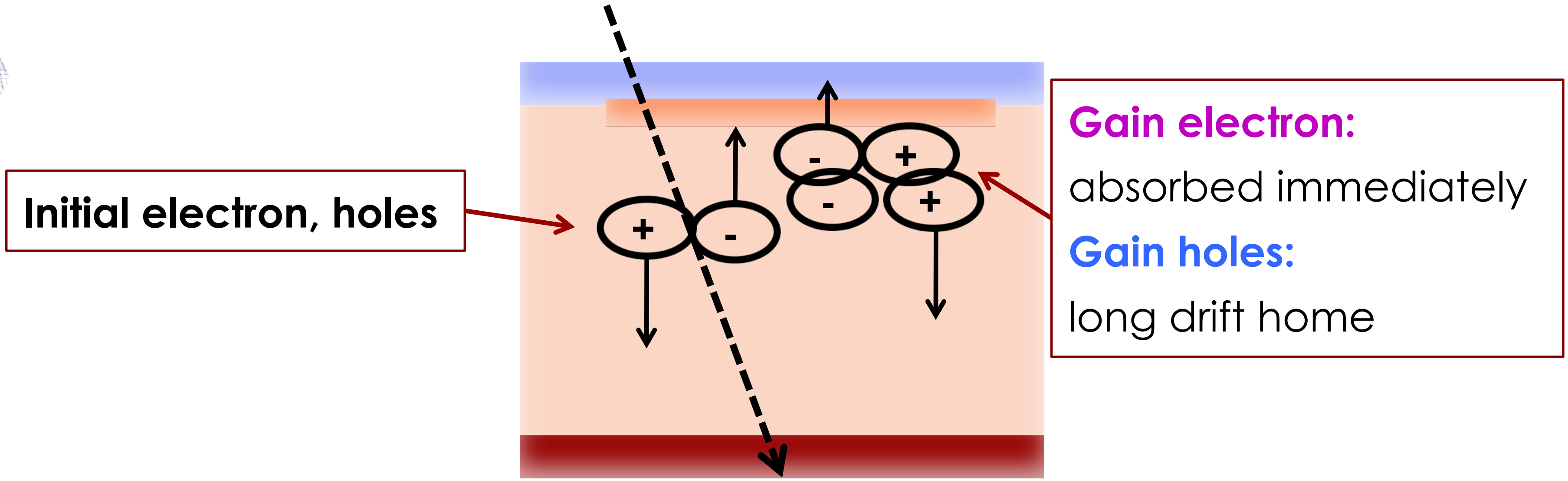
- **Examples of gain layer shapes from a few of our samples.**
- **GL differs for depth and width: both parameters are important.**

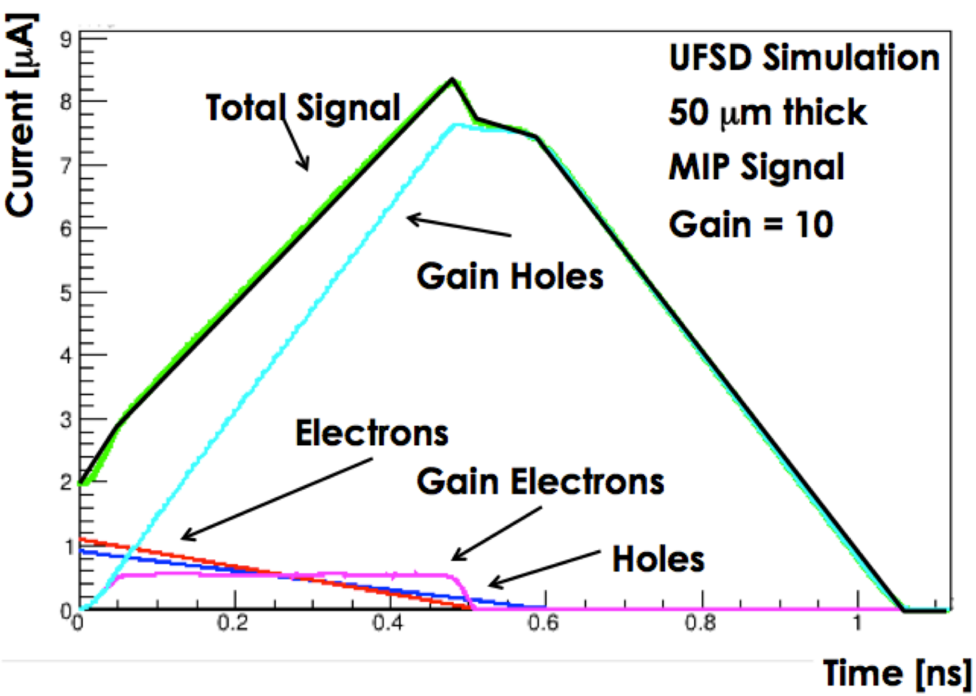
➔ If depth increases, doping should decrease to keep the same gain

A very wide gain layer



How gain shapes the signal





Electrons multiply and produce additional electrons and holes.

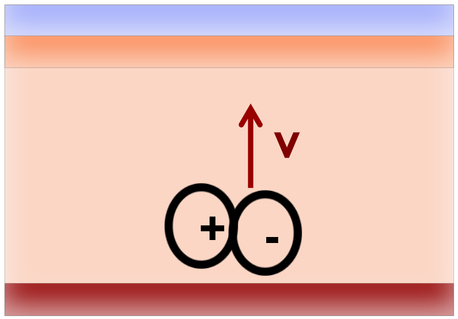
- **Gain electrons have almost no effect**
- **Gain holes dominate the signal**

➔ **No holes multiplications**

Interplay of gain and detector thickness

The rate of particles produced by the gain does not depend on *d* (assuming saturated velocity v_{sat})

Gain



Particles per micron

Gain

$$dN_{Gain} \propto 75(v_{sat}dt)G$$

➔ **Constant rate of production**

However the initial value of the **gain current depends on d** (via the weighing field)

$$di_{gain} \propto dN_{Gain} q v_{sat} (\frac{k}{d})$$

➔ **Gain current ~ 1/d**

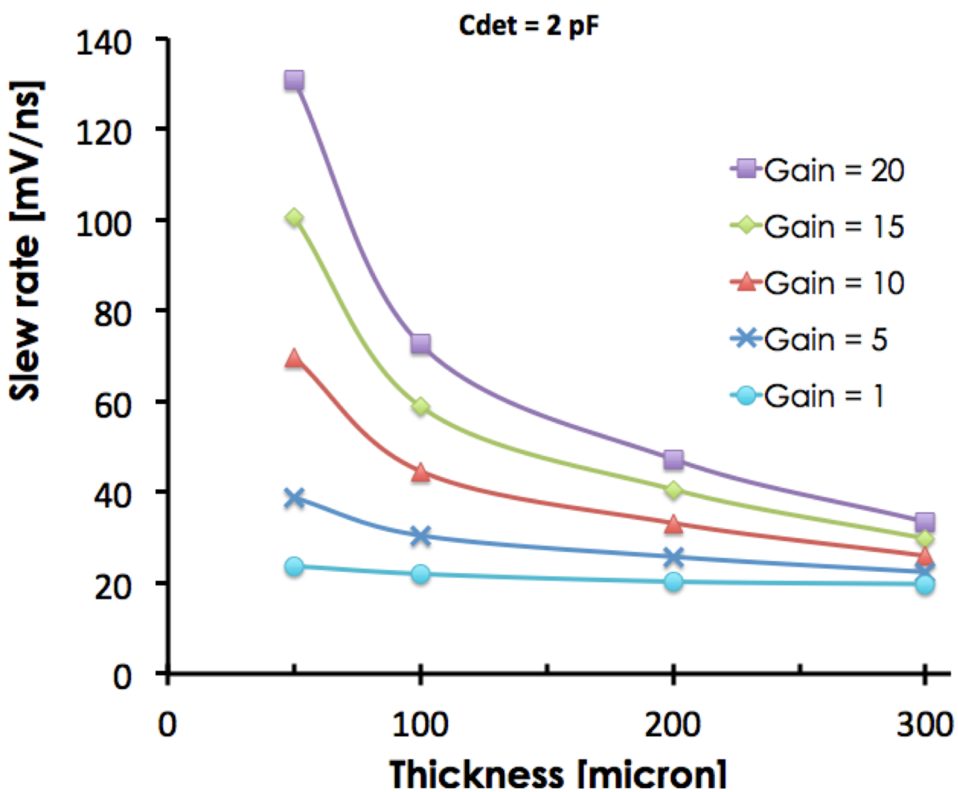
A given value of gain has much more effect on thin detectors

Gain current vs Initial current

$$\frac{di_{gain}}{i} \propto \frac{dN_{Gain} q v_{sat} \frac{k}{d}}{k q v_{sat}} = \frac{75(v_{sat} dt) G q v_{sat} \frac{k}{d}}{k q v_{sat}} \propto \frac{G}{d} dt$$

!!!

➔ **Go thin!!**



(Real life is a bit more complicated, but the conclusions are the same)

Full simulation

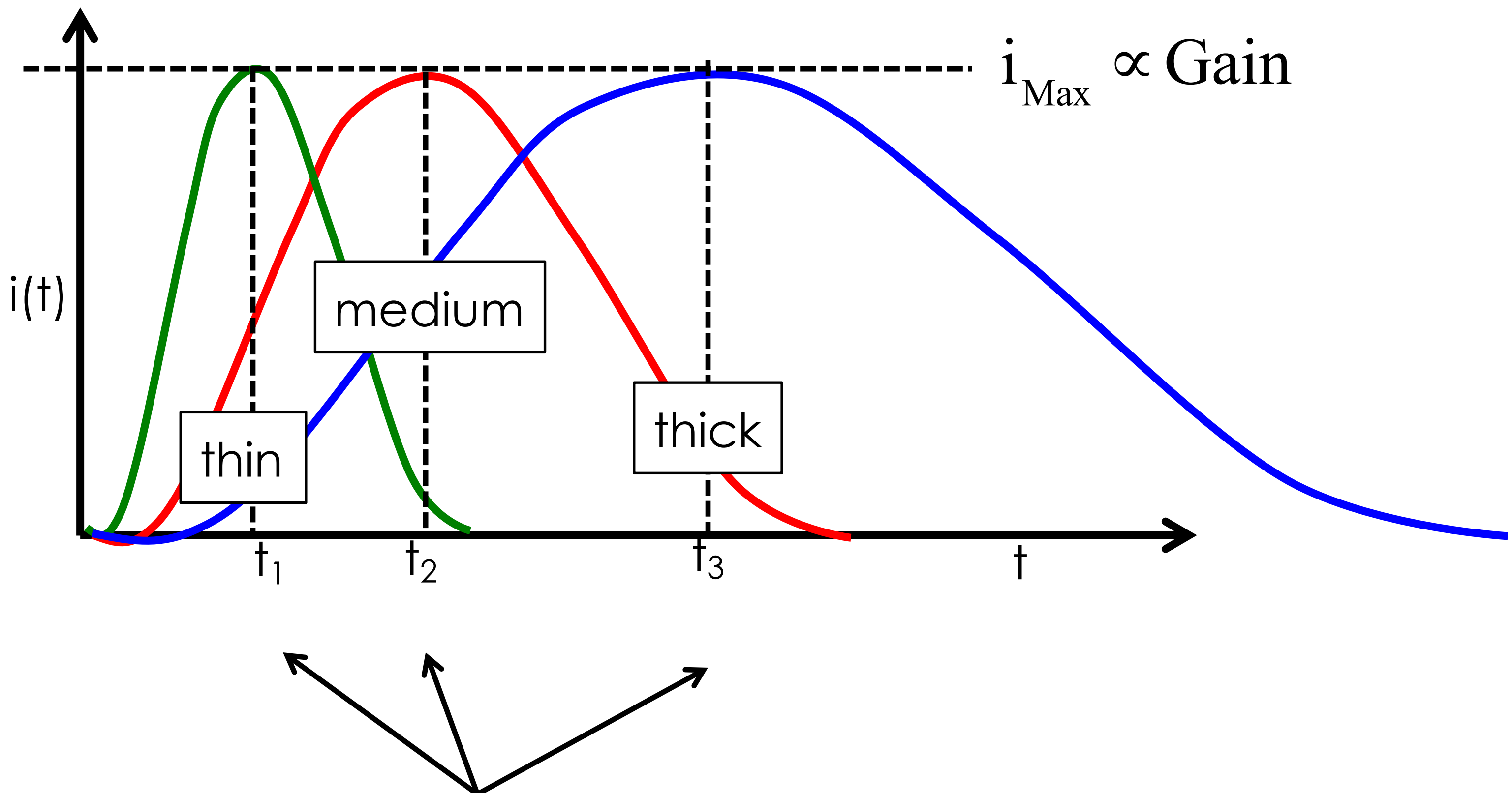
(assuming 2 pF detector capacitance)

300 micron:
~ 2-3 improvement with gain = 20

Significant improvements in time resolution require thin detectors

Gain and Signal current

$$\frac{dV}{dt} \propto \frac{G}{d}$$



The rise time depends only on the sensor thickness ~ 1/d

Ultra Fast Silicon Detectors

UFSD are LGAD detectors optimized to achieve the best possible time resolution

Specifically:

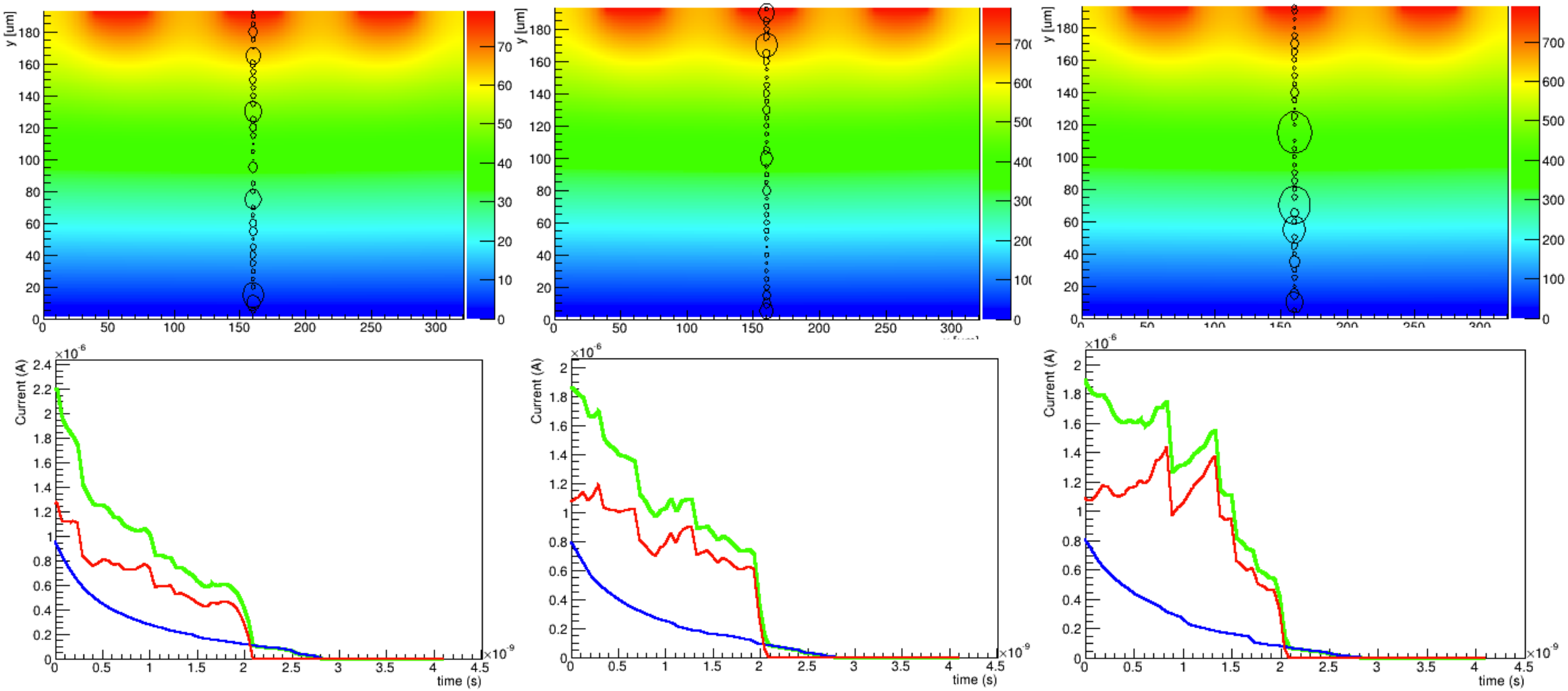
1. Thin to maximize the slew rate (dV/dt)
2. Parallel plate – like geometries (pixels..) for most uniform weighting field
3. High electric field to maximize the drift velocity
4. Highest possible resistivity to have uniform E field
5. Small size to keep the capacitance low
6. Small volumes to keep the leakage current low (shot noise)

Physical limit to time precision: Non-Uniform Energy deposition

Fluctuations in ionization cause two major effects:

- Amplitude variations, that can be corrected with time walk compensation
- For a given amplitude, the charge deposition is non uniform.

These are 3 examples of this effect:



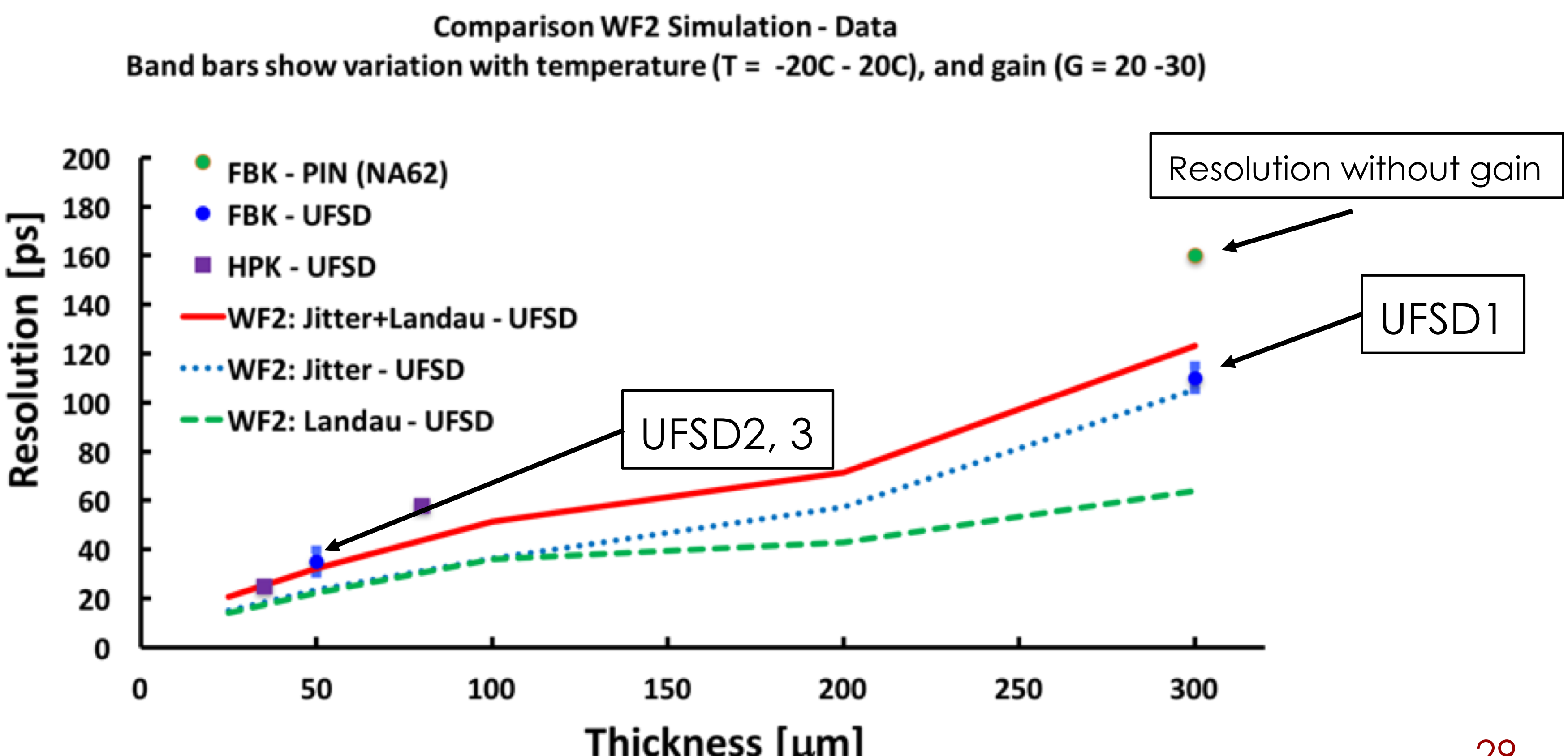
UFSD time resolution summary

The UFSD advances via a series of productions.

For each thickness, the goal is to obtain the intrinsic time resolution

Achieved:

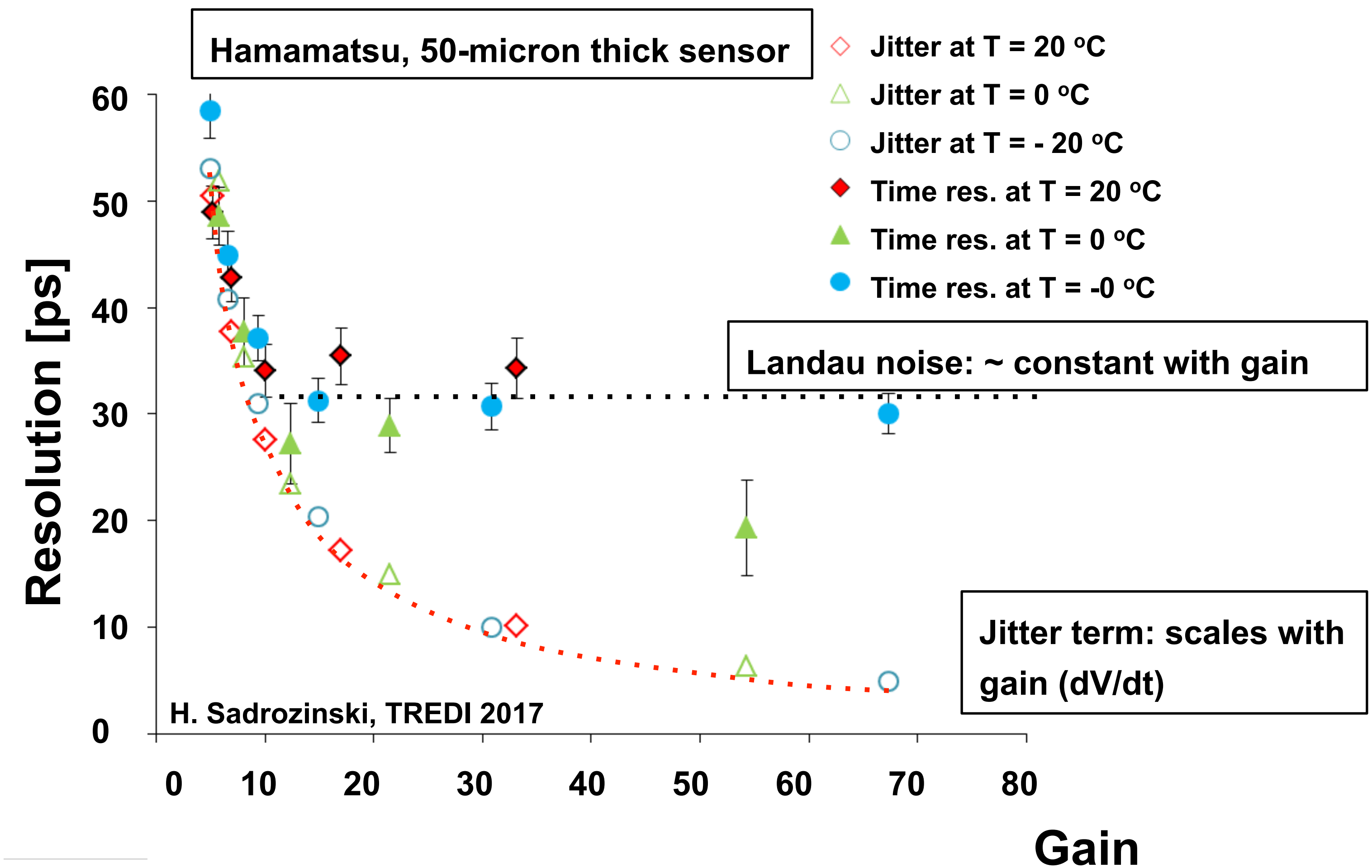
- **20 ps for 35 micron**
- **30 ps for 50 micron**



UFSD time resolution

UFSD from Hamamatsu: 30 ps time resolution,

Value of gain ~ 20

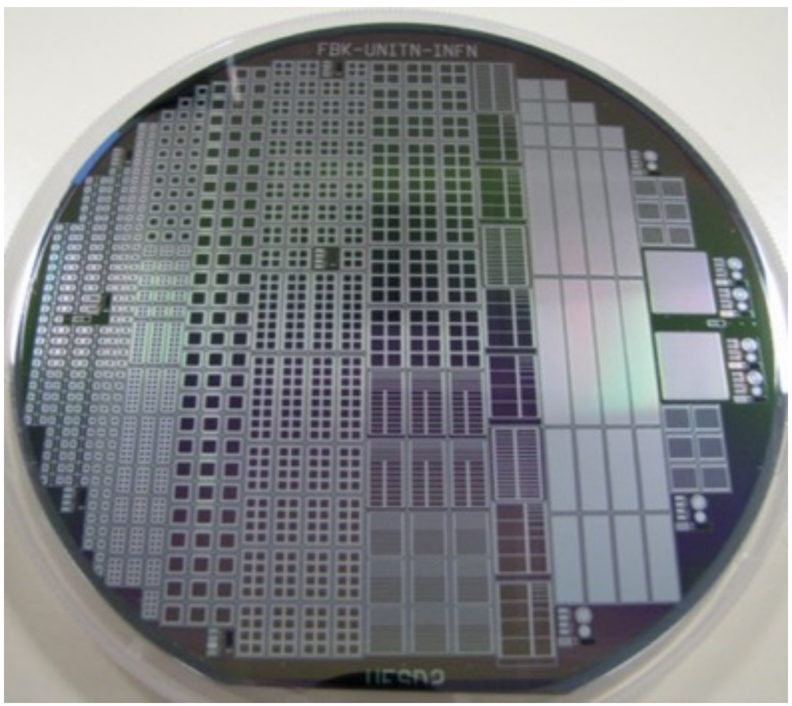


UFSD group: FBK – Trento Uni – INFN-To

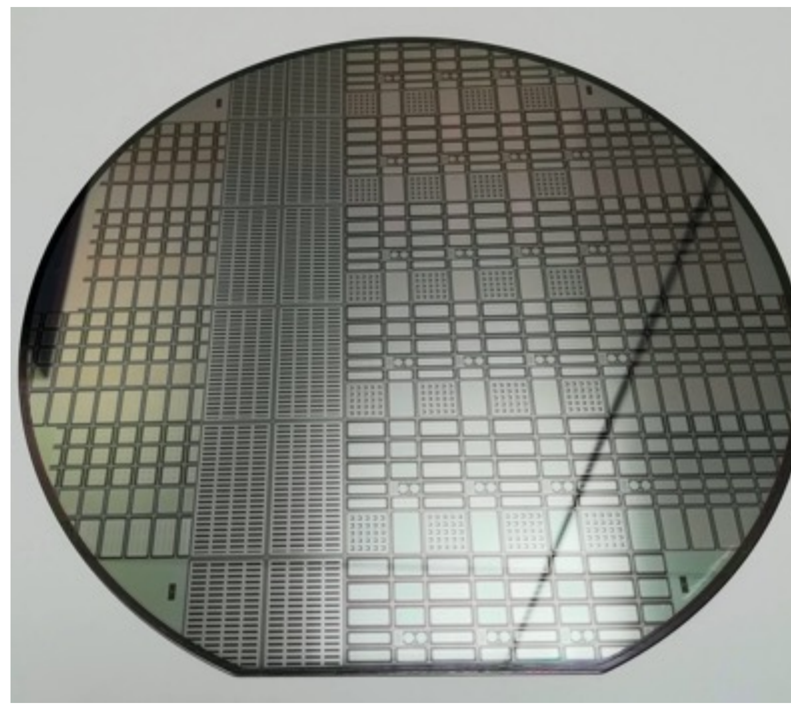
UFSD1: 300-micron. First LGAD production at FBK. Gain layer study, edges

UFSD2: 50-micron. Very successful, good gain and overall behavior, excellent time resolution. Gain layer doping: Boron, Gallium, Boron + Carbon, Gallium+Carbon

UFSD3: 50-micron, produced with the stepper, many Carbon levels, small dead space



UFSD2



UFSD3

Irradiation effects

Irradiation causes 3 main effects:

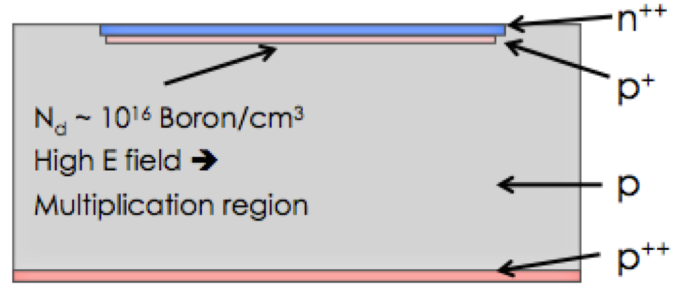
- Decrease of charge collection efficiency due to trapping
- **Doping creation/removal**
- Increased leakage current, shot noise

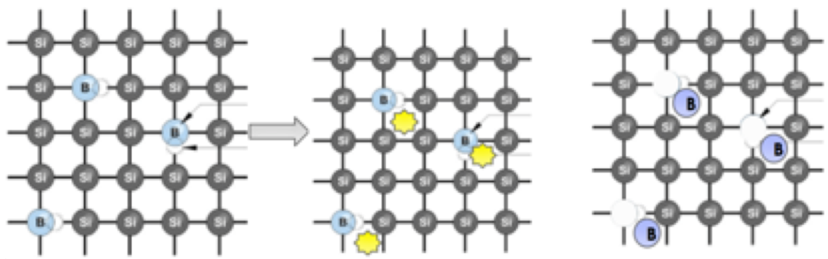
We need to design a detector that is able to survive large fluences, up to ~ 1E15 n_{eq}/cm^2

Acceptor removal

Unfortunate fact: irradiation de-activate p-doping removing Boron from the reticle

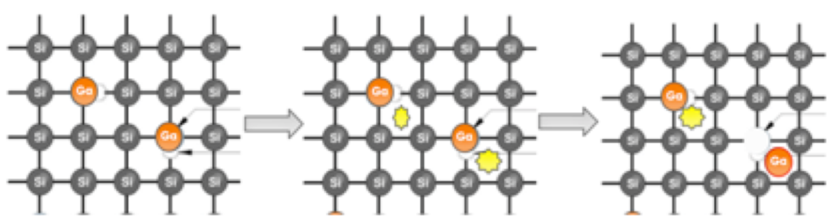
$$N(\emptyset) = N(0) * e^{-c\emptyset}$$



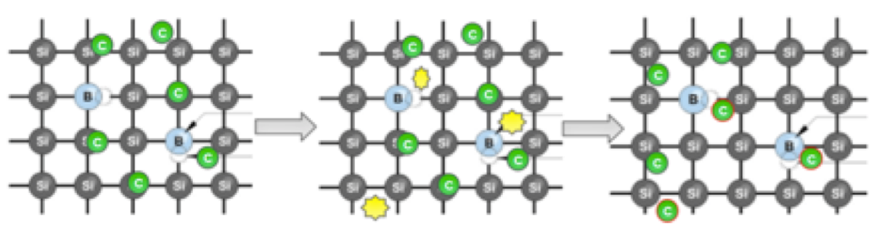


Boron
Radiation creates Si interstitial that inactivate the Boron:
Si_i + B_s → Si_s + B_i

Two possible solutions: 1) use Gallium, 2) Add Carbon

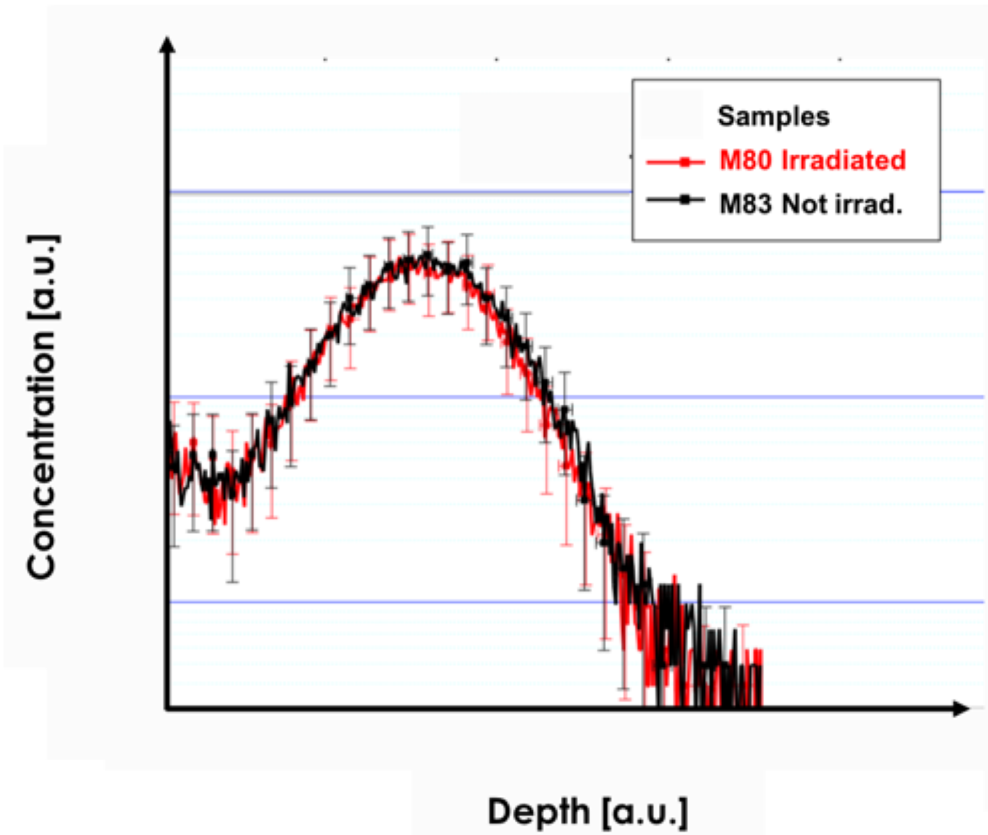


Gallium is substitutional
From literature, Gallium has a lower possibility to become interstitial



Carbon is substitutional
Interstitial Si interact with Carbon instead of with Boron and Gallium

Is the Boron still there?



Yes, **the Boron is still there**, but it is not active any more…

Instead of being "substitutional" (i.e. in the place of a Silicon atom) **is "interstitial"** (i.e. In the middle of the lattice, not electrically active)

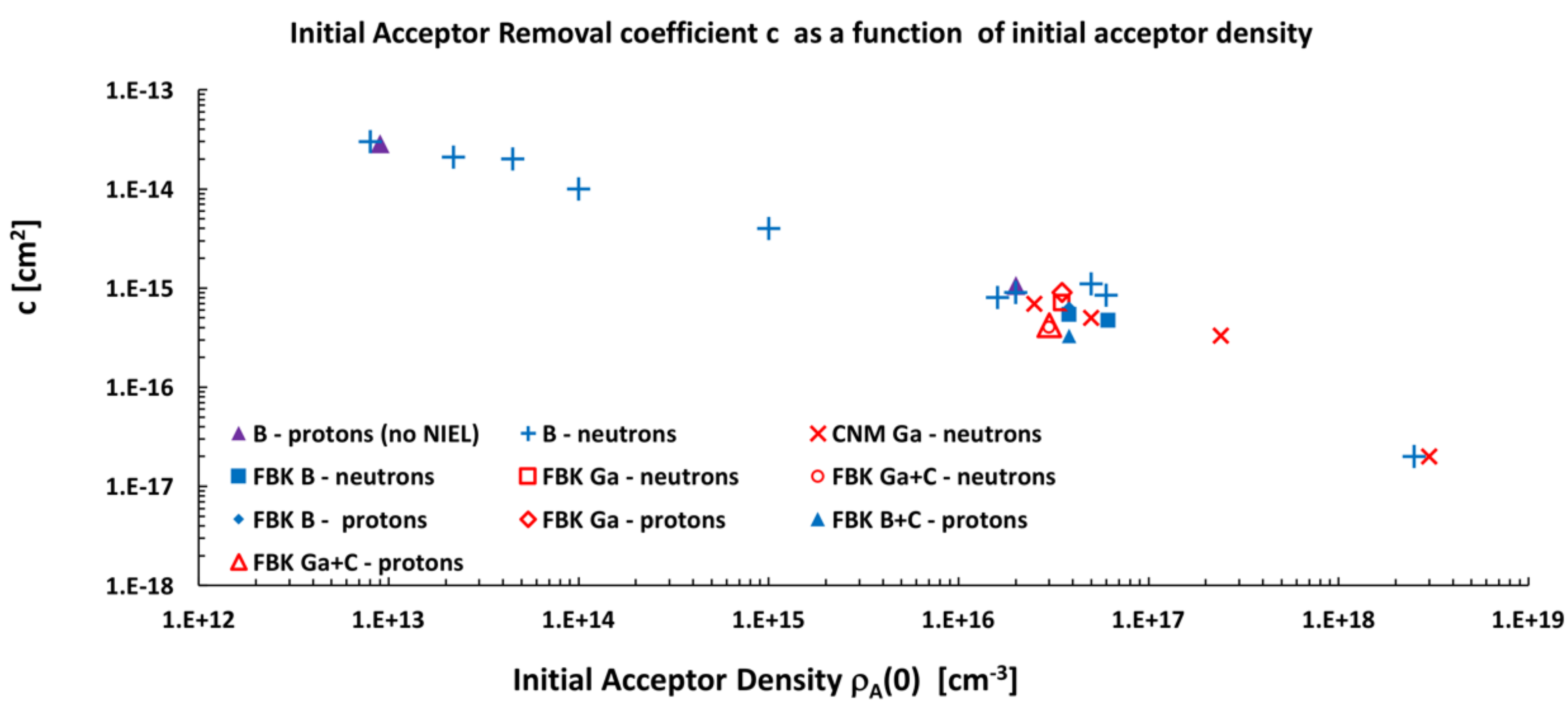
Acceptor removal data

$$N_D = N_0 e^{-c\phi} + \beta\phi$$

Acceptor removal coefficient

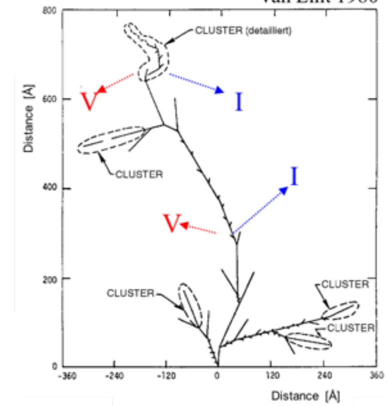
Puzzle: the removal of acceptors depends on the acceptors density

➔ the removal is slower for higher densities



Acceptor removal Model - I

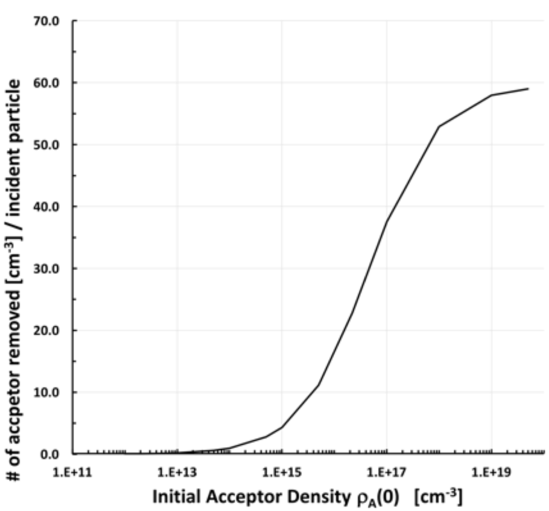
van Lint 1980

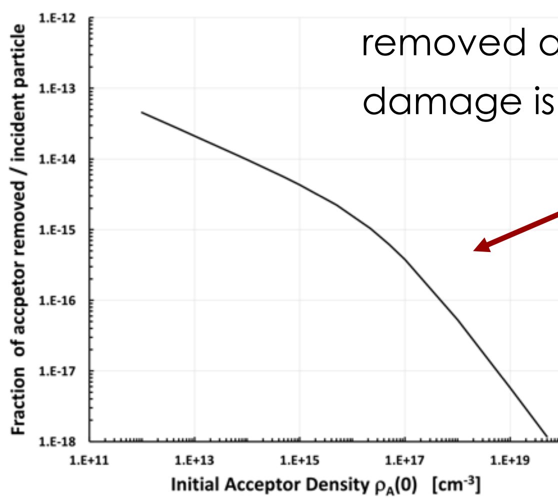


$$N_D = N_0 e^{-c\phi} + \beta\phi$$

Let's write a model for acceptor removal (use neutron as an example):

- A neutron creates a given number of defects, let's suppose 60.
- Each of these 60 defects can remove an acceptor, if there is one in the vicinity
- If the acceptor doping is high enough, each neutron will remove 60 acceptors, otherwise it will remove fewer acceptors





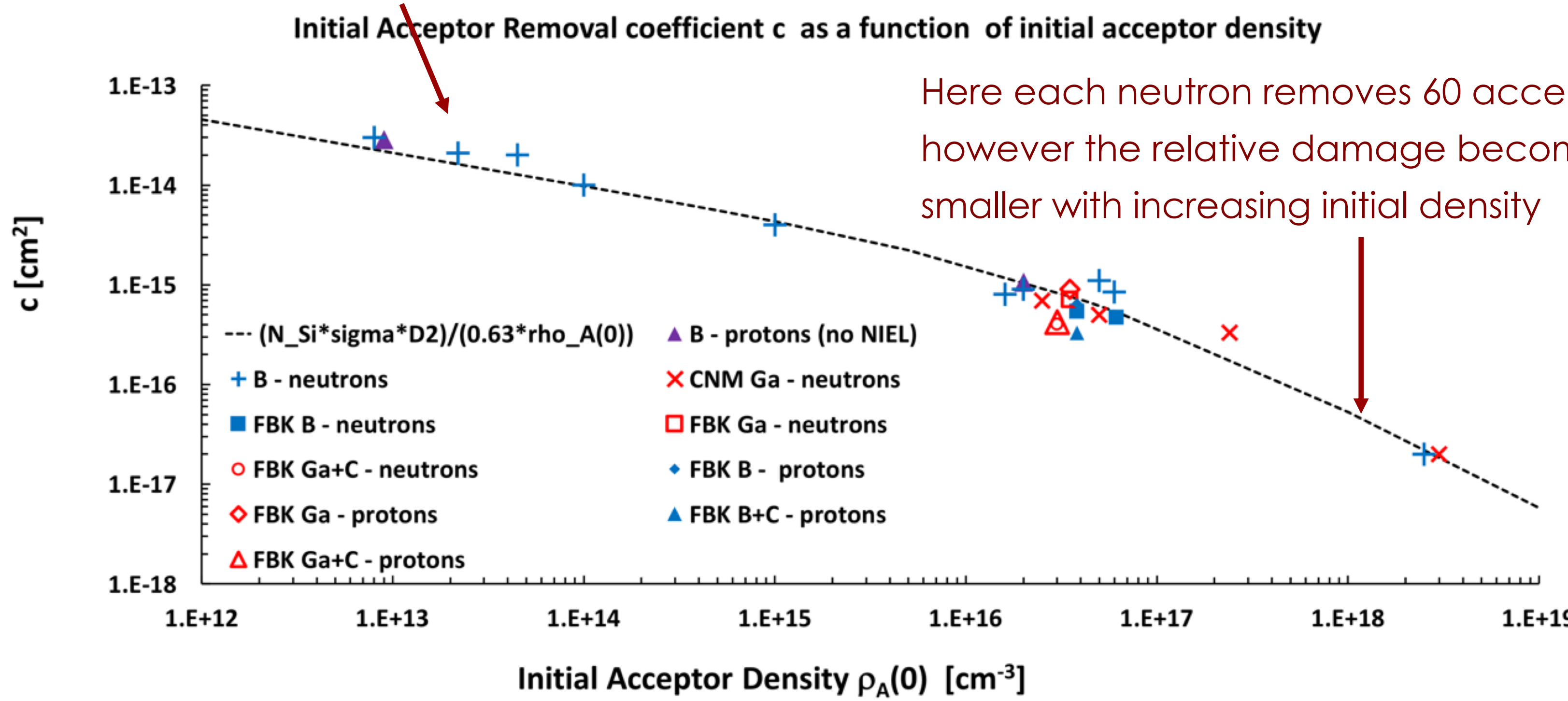
NOTE: Since the maximum number of removed acceptor is fixed, the relative damage is smaller at higher initial density

Acceptor removal Model - II

$$N_D = N_0 e^{-c\phi} + \beta\phi$$

Here each neutron removes fewer acceptors since the initial acceptor density is low (some defects do not find an acceptor)

Here each neutron removes 60 acceptors, however the relative damage becomes smaller with increasing initial density

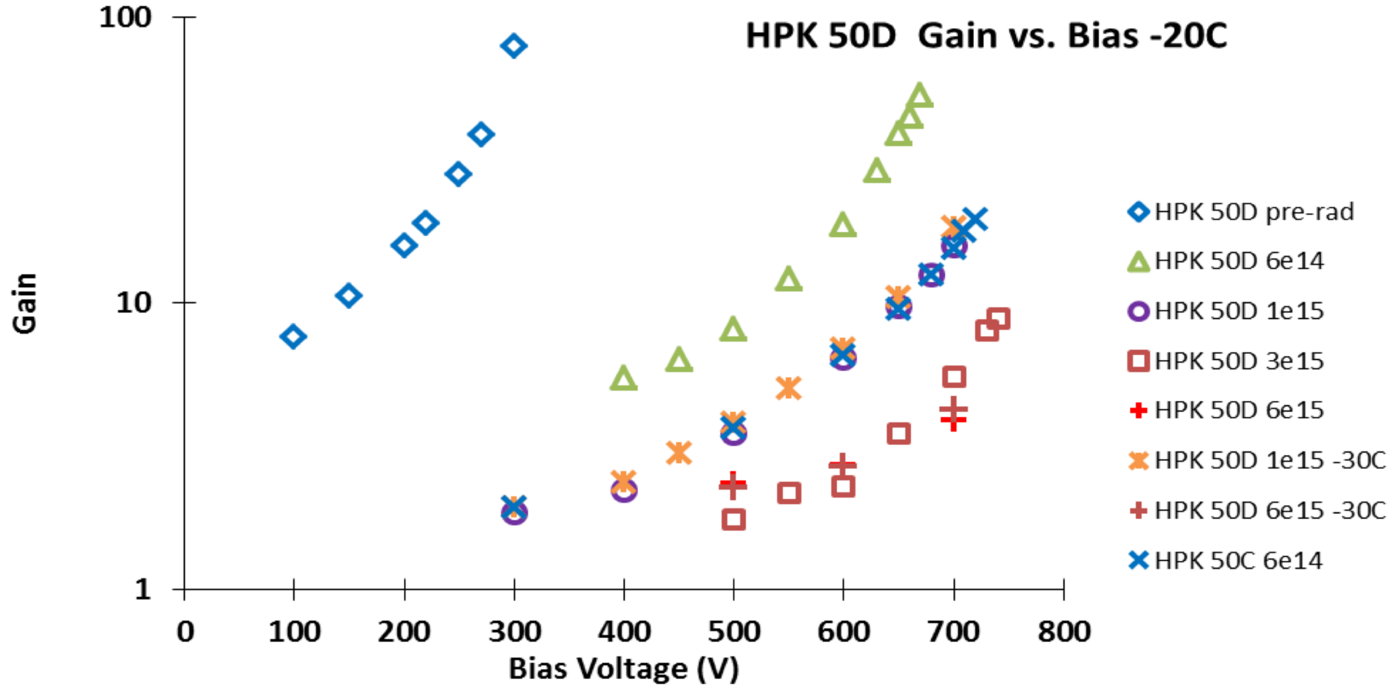


Take home message: if you want a rad-hard sensor, use very high doping levels since they are modified less by radiation effects

Effect of acceptor removal

$$N_D = N_0 e^{-c\phi} + \beta\phi$$

Acceptor removal,
Gain layer deactivation



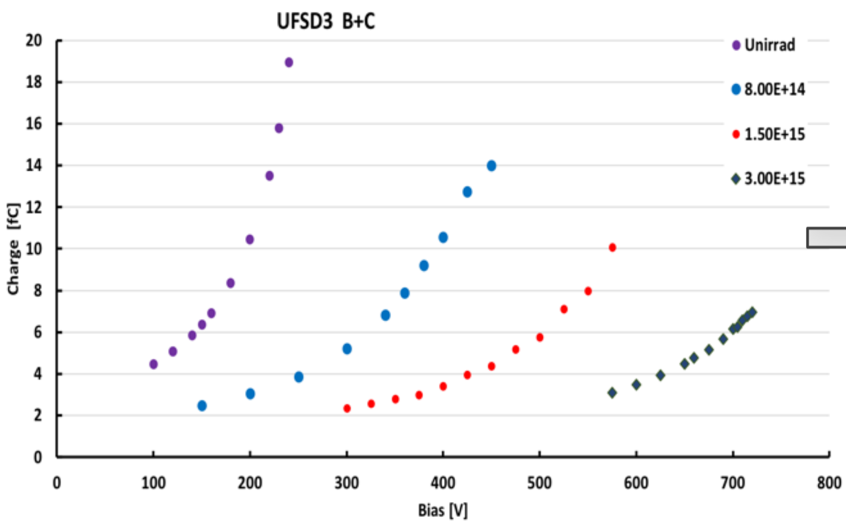
To some extent, the gain layer disappearance might be compensated by increasing the bias voltage

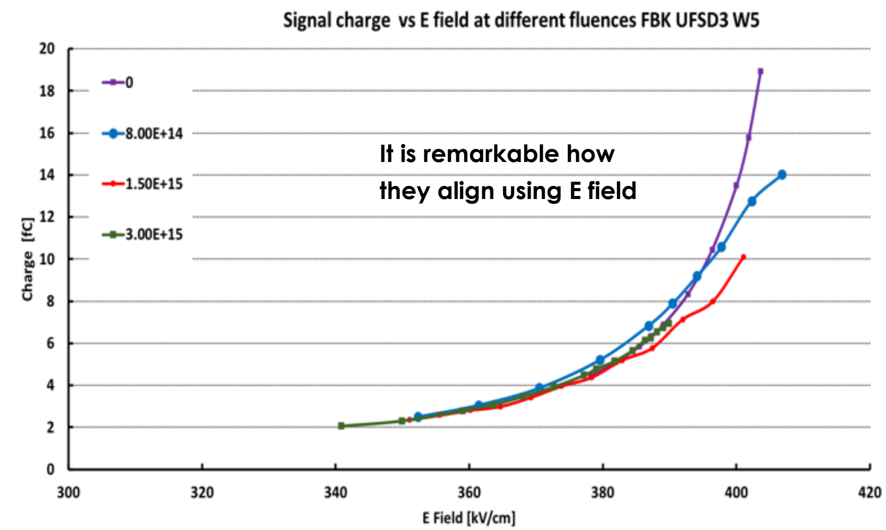
Signal charge, Efield and fluence

The field in the multiplication region is the sum of 3 contributions:

Gain Layer + Bias + Bulk Doping.

We can calculate these 3 components and sum them up





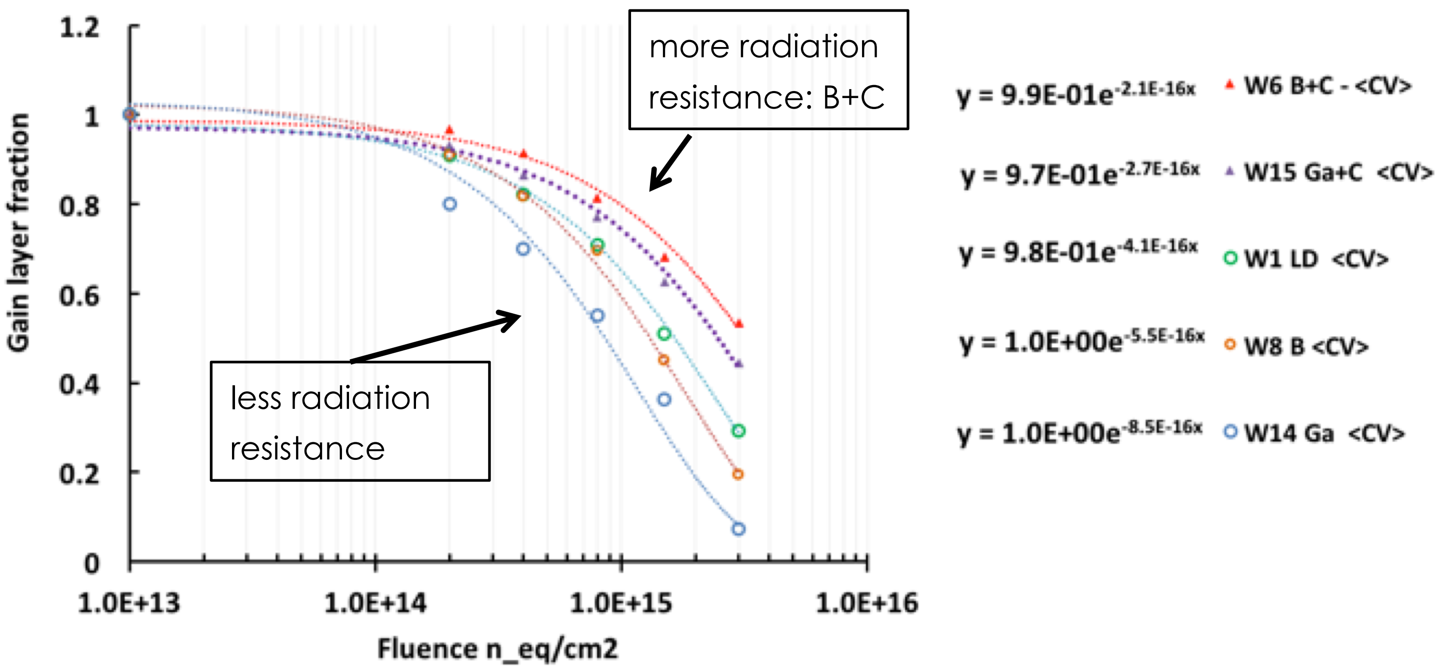
➔ Only function of field, it does not really matter if this field is due to the GL, bias or doping.

➔ Wider gain layers work at lower E field

Impurity engineering of radiation resistance

Let's go back to our model:

- A neutron creates a given number of defects, let's suppose 60.
- **Add: impurities can combine with these defects, reducing their numbers ➔ add impurities**
- Each of these left over defects can remove an acceptor is there one in the vicinity
- **Add: if the energy levels are not favorable, not every defect will remove an acceptor ➔ try change the acceptor, use Gallium instead of Boron**

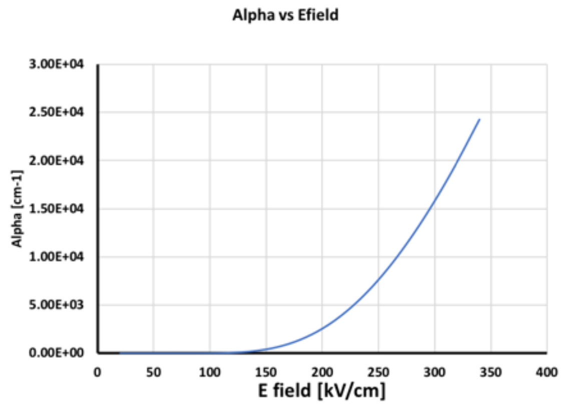


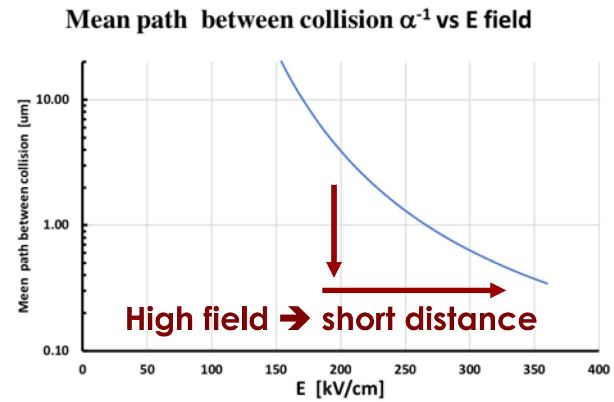
1) **Carbon addition works really well, increasing by a factor of 2-3 the radiation hardness**
2) **Gallium is actually is not more rad-hard than Boron**

Gain and irradiation

$$G \propto e^{\alpha * d}$$

- α^{-1} **(E)** is the necessary distance to acquire enough kinetic energy to start multiplication
- λ is the mean free path between collision

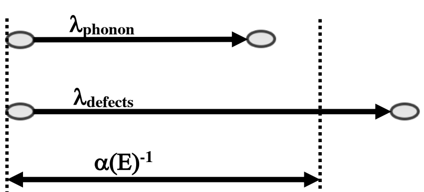




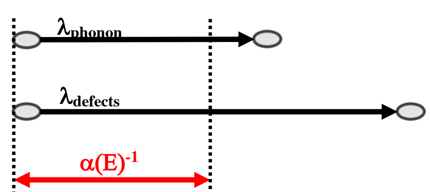
Gain if : α^{-1} **(E)** $> \lambda$

In new sensors, λ is determined by **phonons**

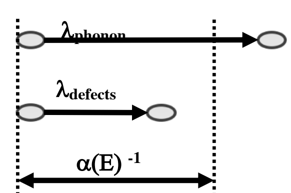
In irradiated sensors, above ???, λ is determined by **impurities: high fluence => no gain??**



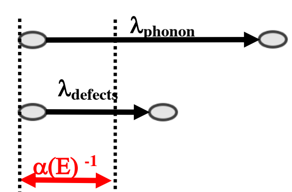
1) Not irradiated high resistivity sensor
Low E field, no gain



2) Not irradiated high resistivity sensor
High E field ➔ gain



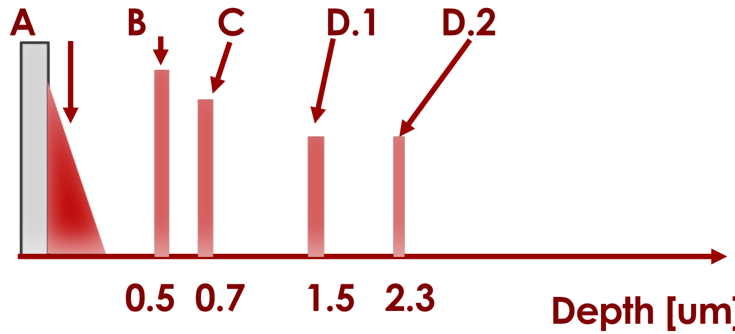
3) Very Irradiated high resistivity sensor
No gain



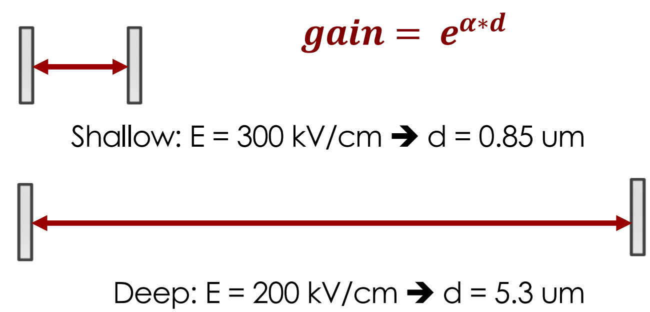
4) Very Irradiated high resistivity sensor
Higher E field ➔ gain

E_{field} vs GL depth vs Radiation Hardness

Gain layer depth: what design is more radiation hard?

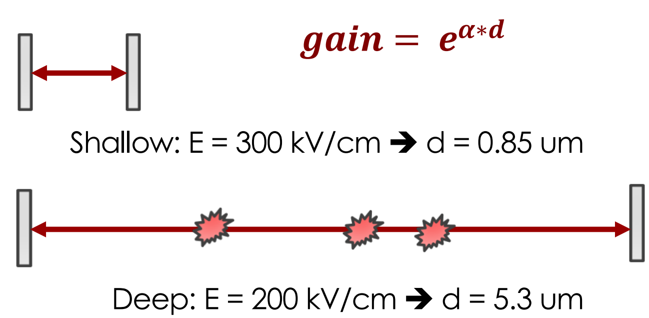


The "shallow" gain layer design has a a higher E field, so it has a lower value of α^{-1} ~ 5 times shorter



Irradiation increases the number of scattering centers decreasing the mean free path

The "shallow" design should to be intrinsically more radiation hard. **Is this true?**



Noise in irradiated sensors

Time resolution in LGAD is determined by jitter and charge non uniformity:

$$\sigma_t^2 = \left(\frac{N}{dV/dt}\right)^2 + \sigma^2_{Non\ Uniform\ Ionization}$$

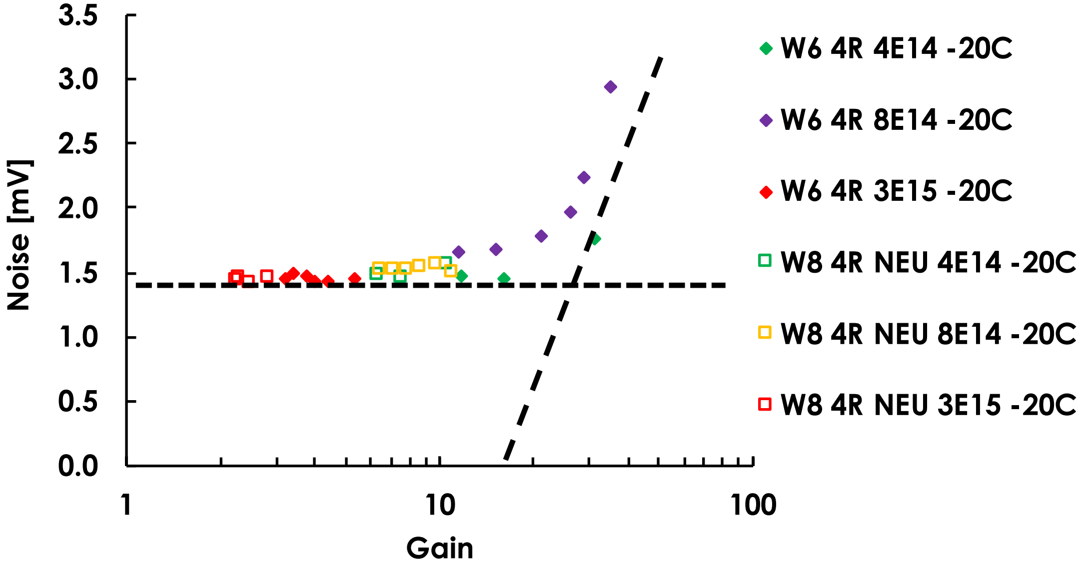
The jitter term contains electronic noise and Current noise:

$$\textbf{Jitter} = \frac{\sqrt{N_{el}^2 + N_{Current\ Noise}^2}}{dV/dt}$$

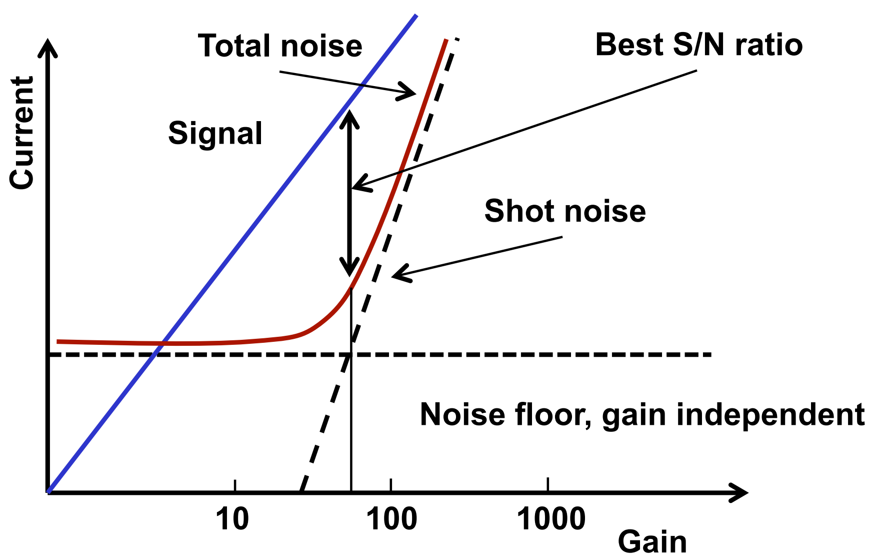
Current noise: noise due to the combination of

- High leakage current ➔ Shot Noise
- Randomness of multiplication mechanism ➔ Excess noise factor

Noise increase as a function of fluence and gain



Data and model look similar.

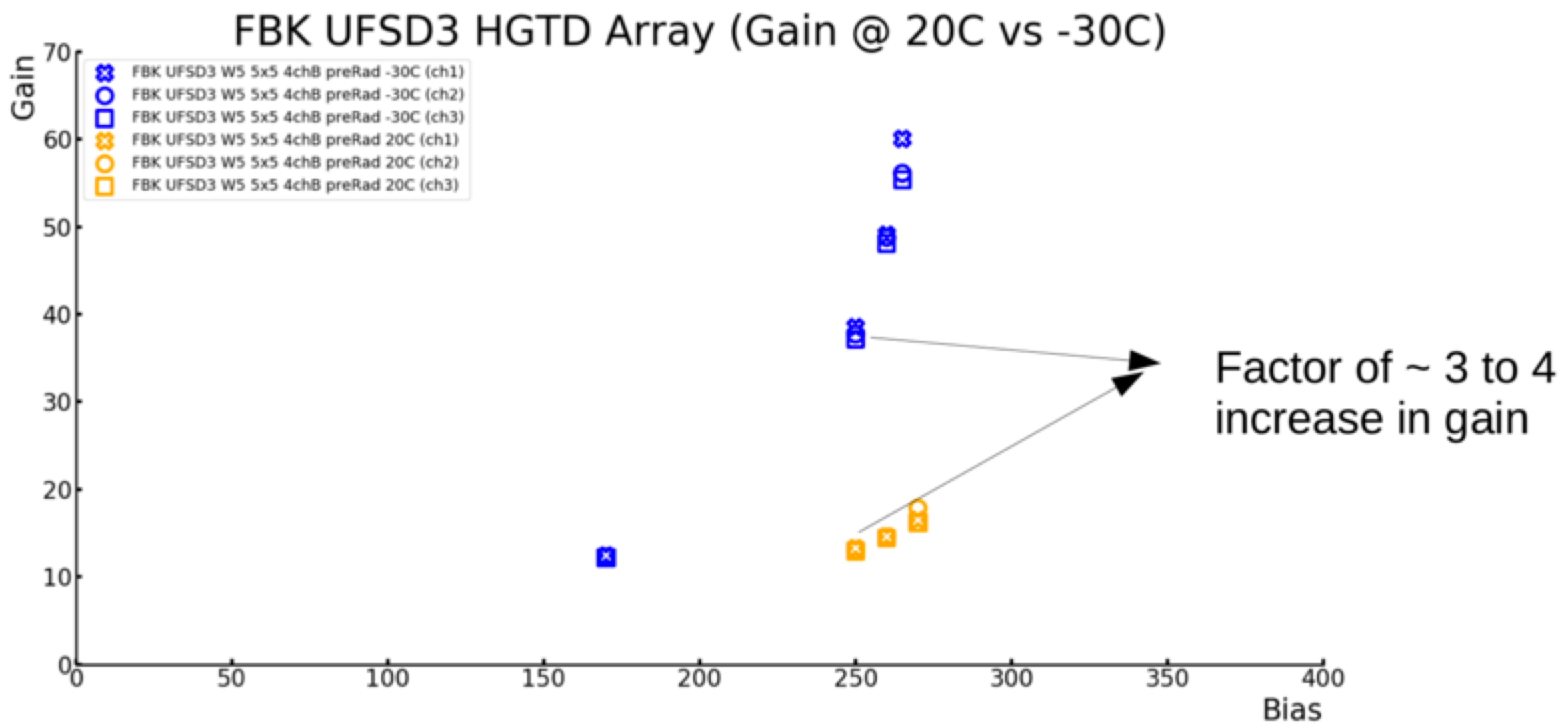


Goal: the noise from Silicon current should stay below that of the electronics

Effect of Temperature: excellent

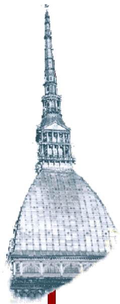
Trackers normally are kept at low temperature, ~ -30 C

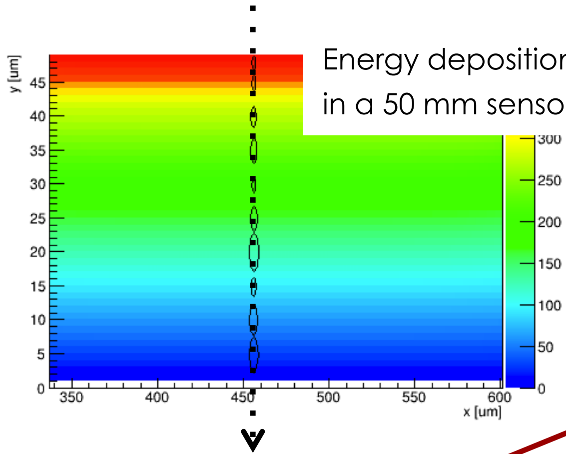
- More gain due to longer mean path between collisions
- Less noise, the leakage current is lower (a factor of 2 every 7 C)



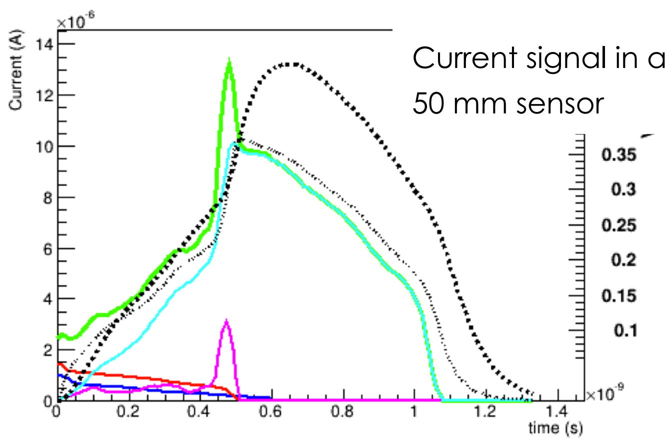
Temperature has a larger effect near breakdown

Electronics: What is the best pre-amp choice?



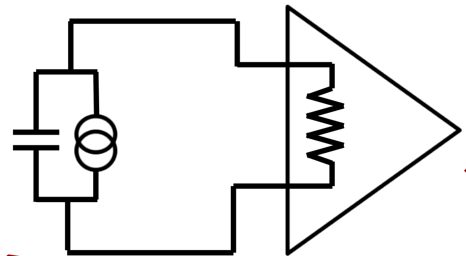


Energy deposition in a 50 mm sensor

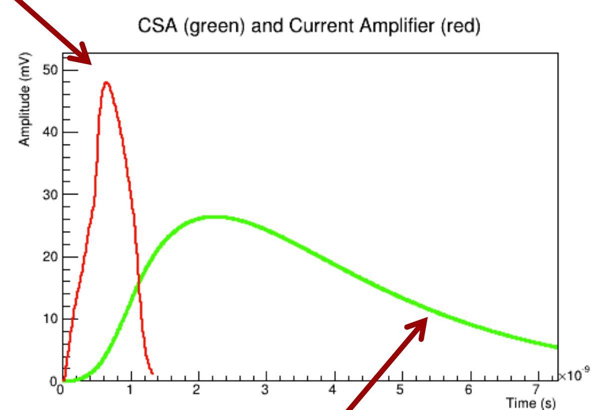


Current signal in a 50 mm sensor

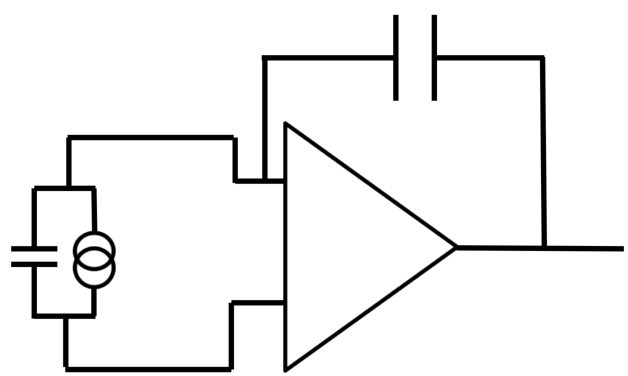
Current Amplifier



- Fast slew rate
- Higher noise
- Sensitive to Landau bumps

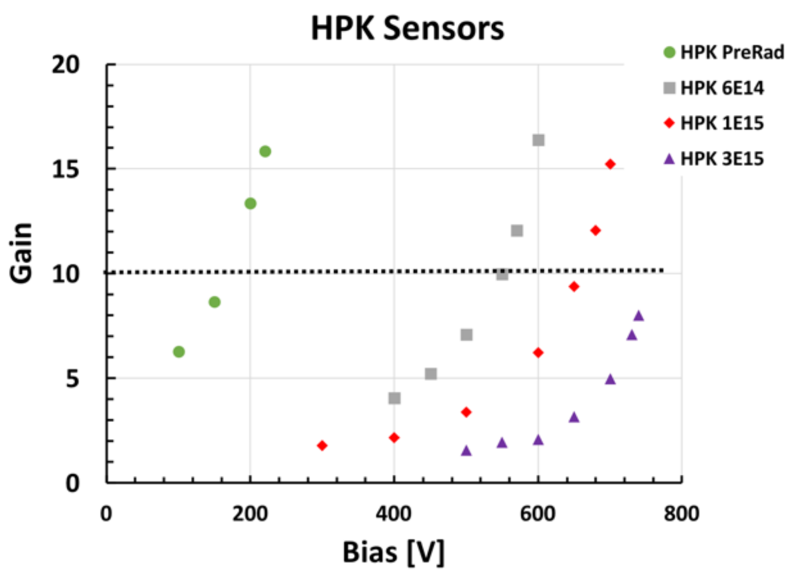


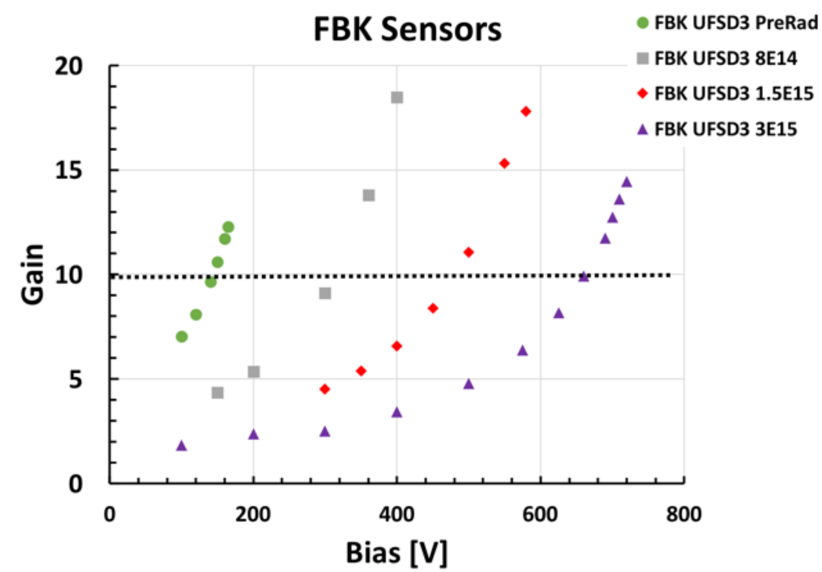
Charge Sensitive Amplifier

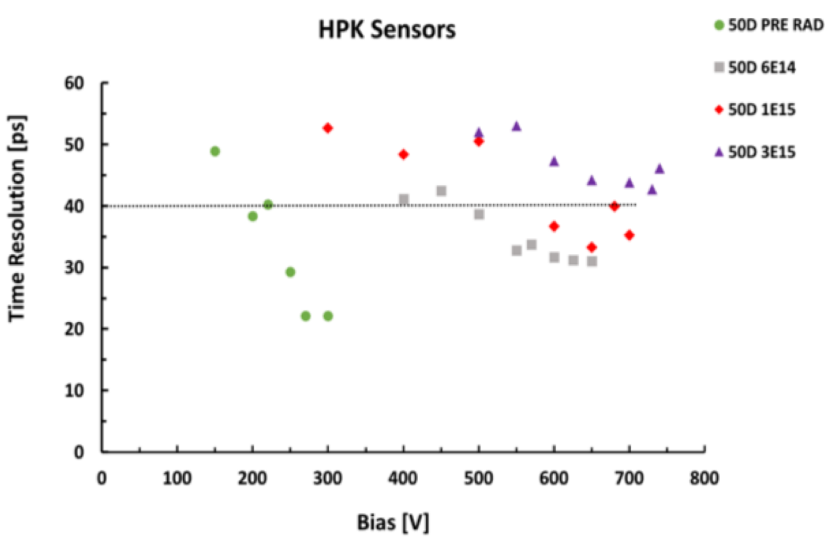


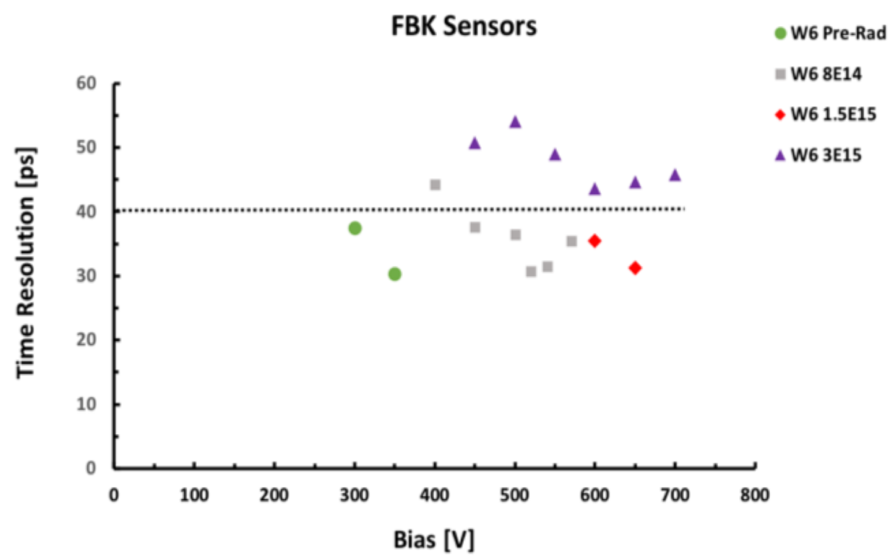
- Slower slew rate
- Quieter
- Integration helps the signal smoothing

UFSD performance









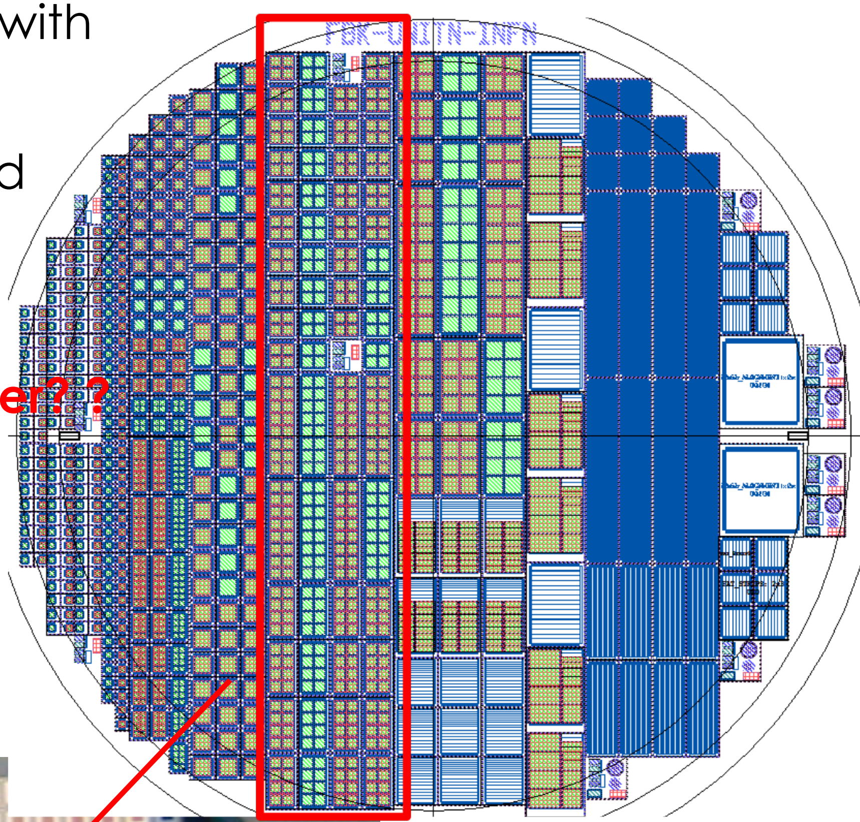
From one pad to a Timing Layer

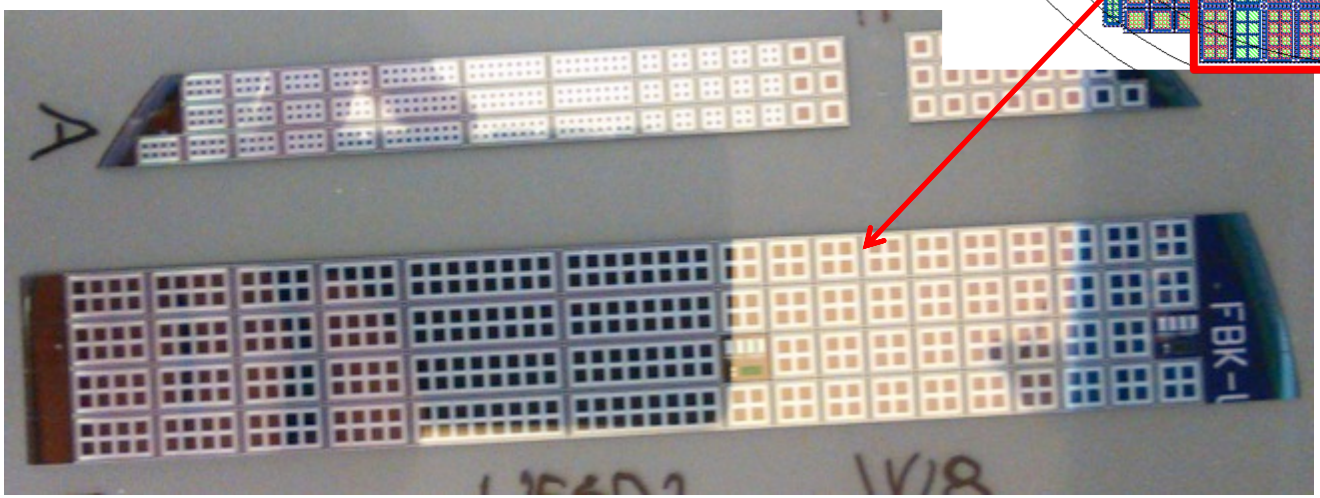
We have produced thousands of UFSDs, with many shapes, thicknesses, gains etc..

We know very well how a single pads and small array work, however….

Are we able to produce a full large tracker? ?

- **Uniformity**
- **Fill factor**

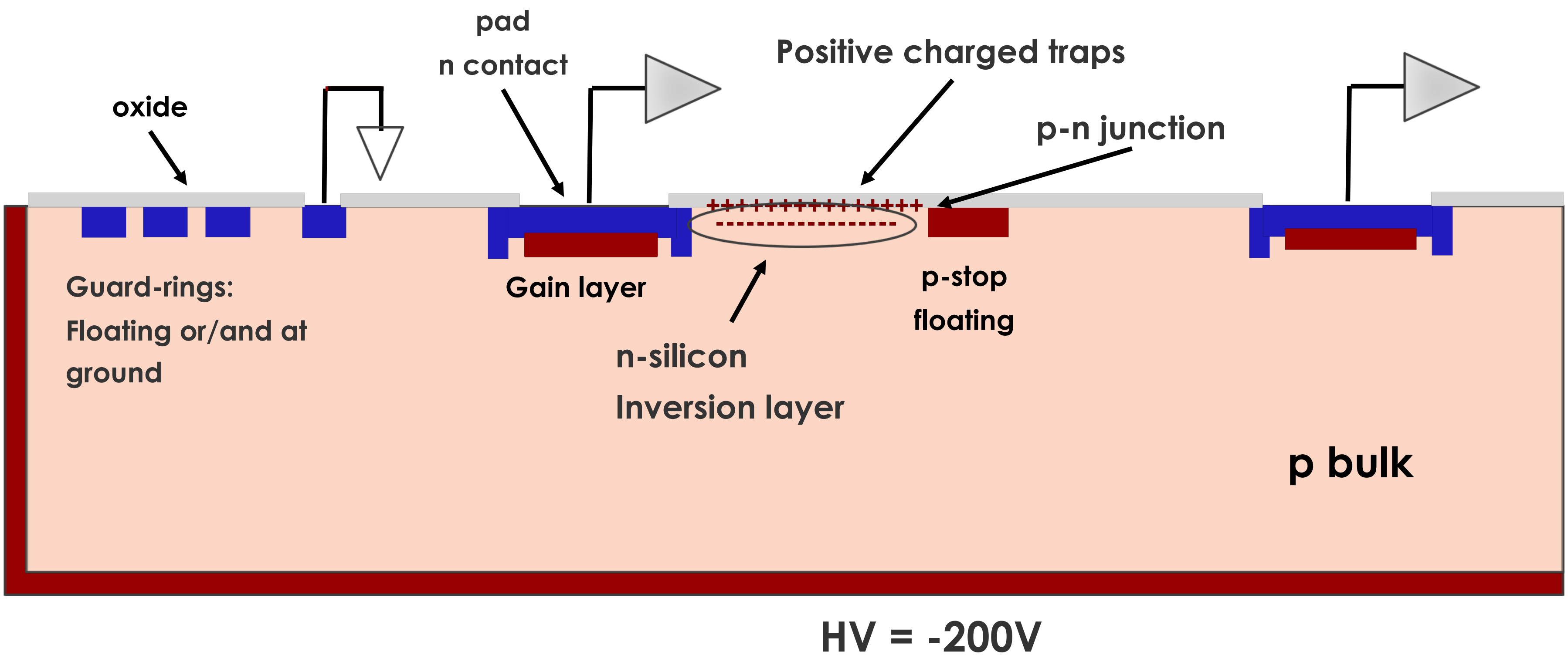




UFSD Multi-pad sensors

Basic building block for a generic UFSD sensor.

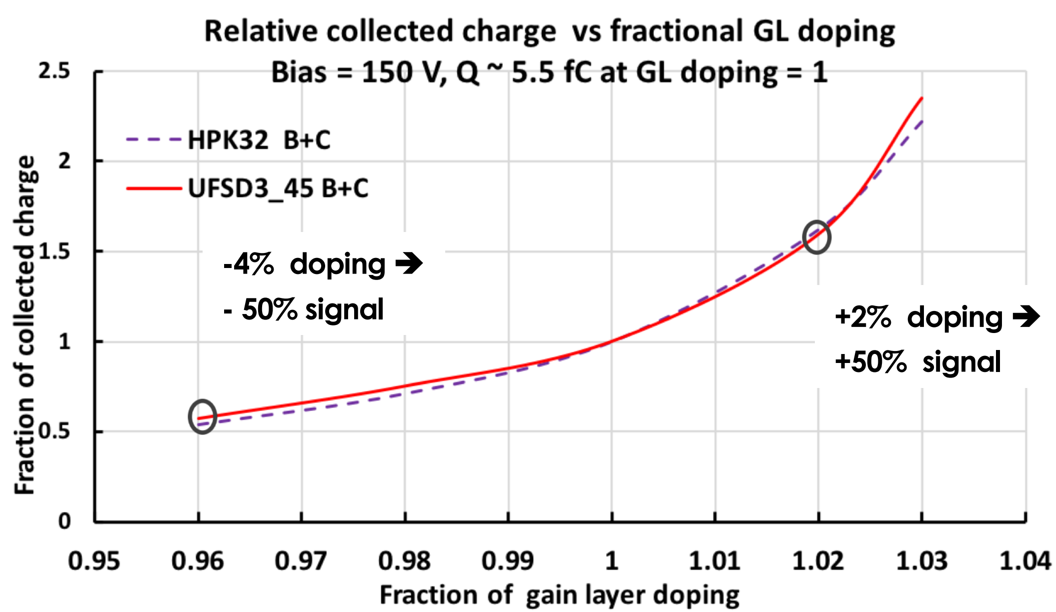
Vendors use proprietary technical variations



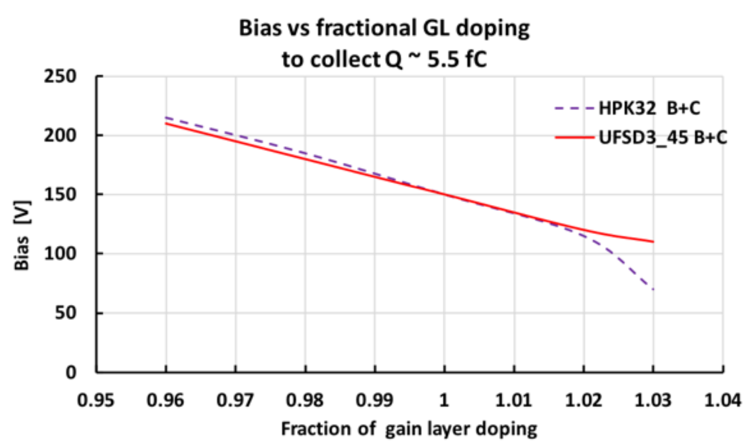
Many years of R&D to define the best geometry

Sensitivity to gain uniformity

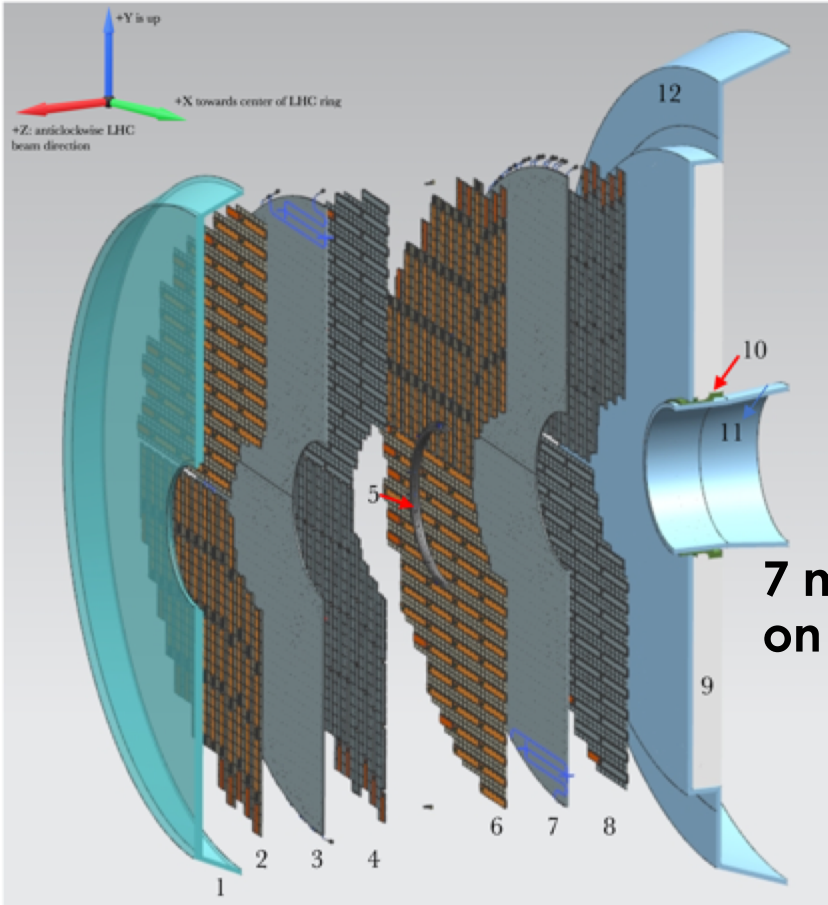
Gain uniformity requires very accurate manufacturing capabilities



The bias can be adjusted to keep the charge constant as the doping in the GL changes.

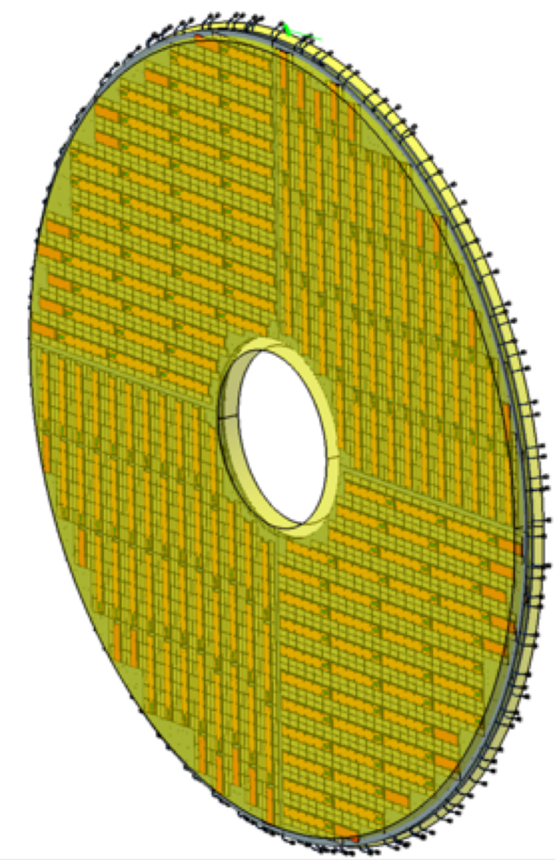


ETL: Endcap Timing Layer



1: ETL Thermal Screen
2: Disk 1, Face 1
3: Disk 1 Support Plate
4: Disk 1, Face 2
5: ETL Mounting Bracket
6: Disk 2, Face 1
7: Disk 2 Support Plate
8: Disk 2, Face 2
9: HGCal Neutron Moderator
10: ETL Support Cone
11: Support cone insulation
12: HGCal Thermal Screen

7 m² of sensors on each side



A circle obtained with long staves

~ 16000 sensors:

- 2x4 cm² --- small sensors
- Thickness of active area: 40-50 microns
- Pad size: 1.3 x 1.3 mm² (512 pads)

Fill factor

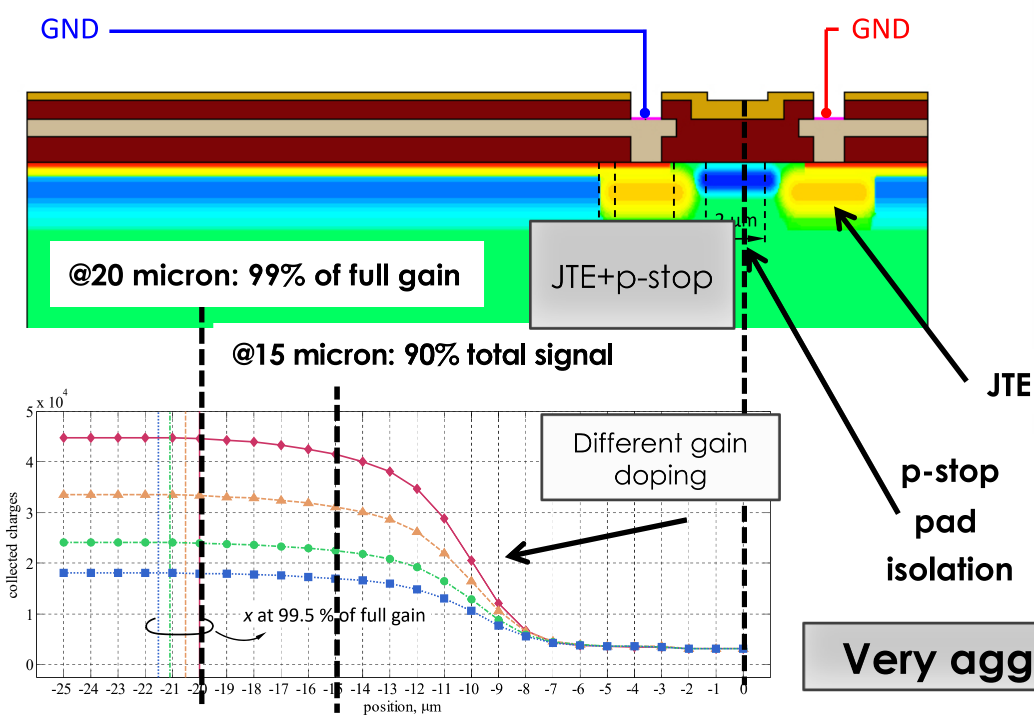
The gap is due to **two components**:

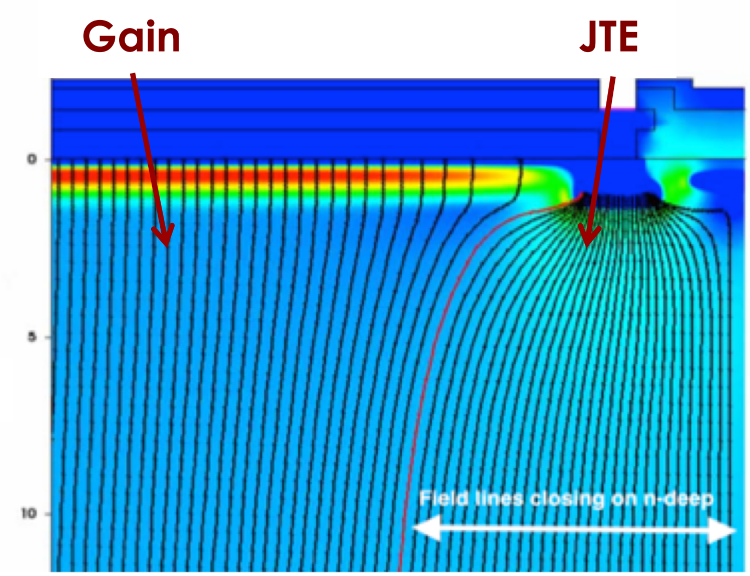
1) Adjacent gain layers need to be isolated (**JTE & p-stop**)

2) Bending of the E field lines in the region around the JTE area

Both under optimization Different junction termination/p-stop design

- **CMS Goal: 30 micron gap = 96% fill factor**



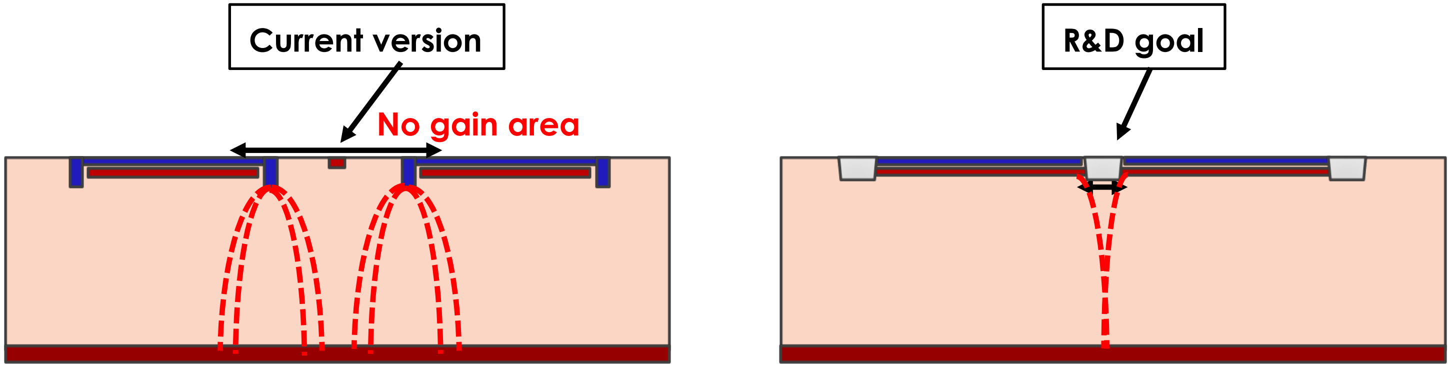


Very aggressive design: <10 micron per side

Fill factor solution: trenches

Trenches (the same technique used in SiPM):

- No pstop,
- No JTE ➔ no extra electrode bending the field lines



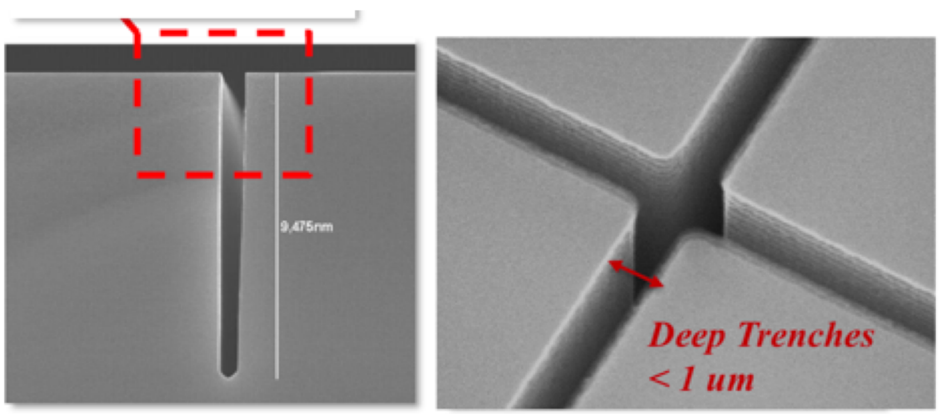
JTE + p-stop design

Trench design

Trench isolation technology

- Typical trench width < 1 um
- Max Aspect ratio: 1:20
- Trench filling with: SiO_2, Si_3N_4, PolySi

CMM
CENTRE FOR MATERIALS AND MICROSYSTEMS



5D tracking: 4D tracking + very high rate

One last twist of complication:

4D tracking at very high rate requires multiple TDC per bin, very high data transfer and a lot of power.

Unfortunately, as soon as you say: “we can do 4D tracking”, the community asks for high rate too…

Summary and outlook

Timing layers, 4D- and 5D- tracking are being developed for the next generation of experiments

It is a challenging and beautiful developments, that requires a collective effort to succeed.

There is no "one technology fits all": depending on segmentation, precision, radiation levels and other factors the best solution changes.

It would be great if in our journey we stumble upon a highway, to take us out of the desert

Full bibliography:
http://personalpages.to.infn.it/~cartigli/NC_site/UFSD_References.html